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A Review of Carbon Capture and Sequestration in Iran: Microalgal Biofixation Potential in Iran

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ABSTRACT

The continuous rise in CO_2 and global warming is a major issue facing the world today. Iran with annual CO_2 production of 532.4 million tons in 2010 has been reported to be the 9th country in the world. Shortage, low efficiency, losses, subsidies and unsuitable consumption pattern in sub-sectors challenge Iran's energy sector. Country's energy supply is intensively dependent on oil and gas, which lead to produce more greenhouse-gas emission. Therefore, Iran should establish some policies to control its environmental pollutions and place carbon-mitigation strategy within the government agenda as soon as possible. Efficient use of energy, progress of renewable energy and enhancing CO_2 sequestration to mitigate more CO_2 can be alternatives for reduction of greenhouse-gas emissions. Regarding major geological formations such as the second largest natural-gas reservoir and the third-greatest oil reservoir in the world and the second largest basin in the Middle East, storage of carbon and enhanced oil recovery seem to be a suitable choice for carbon capture and storage. Moreover, in Iran due to a vast land area, presence of various saline lakes which containing different species of microalgae and opportunity of establishing microalgae culture ponds, the capture unit and microalgal culture can be located close to carbon sources, which are scattered and far from geological formations. Besides CO_2 mitigation, microalgae cultures can also produce valuable products and cause carbon capture more efficient. This article with the aim of anthropogenic CO_2 reduction, reviews programs in the field of energy management and sustainable energy development to control emission. Then carbon sources and the potentials to capture and sequester CO_2 are explored. In the end, potentials of microalgae in Iran to mitigate CO_2 are described. This review is designed to investigate abilities in Iran to utilize or minimize CO_2 and deploy biological carbon sequestration in the context of Iran's policy environment.

Contents

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1. Introduction

Increasing concentrations of greenhouse gases in the atmosphere are enhancing the natural greenhouse effects which cause a change in the climate and rise in the global average temperature. Now, it is generally accepted that limits should be placed on greenhouse gases' concentration in the atmosphere [1]. Carbon dioxide among greenhouse gases has become the focus of attention due to its amount present in the atmosphere which has a contribution up to 60 percent of global warming effects, and it is viewed as a potential agent of global climate change [2–5]. Recently, Bacon et al. [6,7] found that CO_2 is responsible for as much as 58.8% of total greenhouse-gas emissions.

Since pre-industrial years, until now, CO_2 concentration in the atmosphere has increased from 280 ppm to more than 393 ppm and caused about 75% of the expected 1 °C warming [6,7]. It is predicted that by the year 2100, the atmosphere may contain up to 570 ppm CO_2 and causing a rise in global temperature of around 1.9 °C and an increase in mean sea level of 3.8 m [8]. Even a much higher temperature increase about 1.4 to 5.8 °C is predicted [9–12]. Moreover, because of an absorbing one-third of the CO_2 emitted each year marine ecosystem biodiversity in the oceans is affected by turning the water pH to be more acidic [13,14]. Global CO_2 emissions represent a growth rate of more than 4.6% between 2009 and 2010, which increased by 1.3 Gt CO_2 because of the impact of the financial crisis particulary in Western economies [15,18].

The growth rate of CO_2 emissions is proportional to the world's population growth rate [16]. Therefore, CO_2 concentration in the air is estimated to increase by 75 ppm during 2000–2050 and that the levels of CO_2 greater than 450 ppm could be destructive to the world's global climate and would be "dangerous" [17]. International Energy Agency (IEA) reported for the first time in 2008 the aggregate emissions of the developing countries were larger than those of the developed countries. CO_2 emissions of developing countries in 2011 continued to increase at a faster rate than in the developed countries, mainly due to growing fossil-fuel consumption in some of the larger countries. IEA Greenhouse Gas R&D Program reported the emissions of CO_2 may need to be reduced by more than 60% by 2010 to stabilize the atmospheric concentration of CO_2 at no more than 50% above its current level [18].

Therefore, energy policies in all countries must be forced to decrease carbon dioxide emission in a future, especially in ten countries, which producing more carbon dioxide. Regionally, CO_2 emissions in the Middle East increased significantly by more than 4%. In this region, Iran is the greatest emitter of CO_2 emission and is located in the list of the top 10 emitting countries accounting for about two-thirds of the world CO_2 emissions. Iran is the 9th-largest emitter of total greenhouse gases in the world in 2010. CO_2 has increased from 492.3 million tons in 2007 to about 532.4 million tons in 2010, showing a growth of 8.14 percent between these years. However, during the long period between 1990 until 2010, CO_2 has a growth rate of 174%.

The power-generation sector alone has contributed to more than 29.1 percent of the total CO_2 in 2010. The bulk of Iranian greenhouse-gas emissions, 54.1%, come from power plants and domestic sectors, mainly through the expansion of energy demand. During this year, emission from power plants was about 154.8 million tons and emissions from industry and refinery sectors were about 88.6 and 17.2 million tons, respectively. In according to the average annual growth rate of CO_2 in power plants, it is anticipated that CO_2 from power plants and all sectors in 2025 will reach to 247 and 930 million tons, respectively, which are alarming figures [19].

Since CO_2 is closely related to economic development, economic growth plays a focal role in the environmental pollution. Yousefi-Sahzabi et al. [20] found a significant relationship between CO_2 emission and economic growth of Iran over 14 years from 1994 to 2007. The economy of Iran is the eighteenth greatest in the world by purchasing power parity (PPP) in 2010 and according to its officials' claims is going to become the 12th largest by 2015 [21,22]. As a result, CO_2 in Iran will continue to grow unabated, albeit at a lower rate.

Apart from economic growth, Iran's demographic profile is sharply youth oriented and this upcoming generation's needs for employment and housing, couples with low energy-efficiency vectors and consumption patterns. Moreover, Iran has the energy consumption extraordinarily higher than international standards. Its energy consumption per capita is 15 times that of Japan and 10 times that of European Union [23]. All of these have created a constant rise in energy demand, energy consumption and greenhouse gas (GHGs) emissions in the residential sector.

Thus, CO_2 mitigation from the air should become a significant part of Iran's future policy and development as an important long-term air treatment strategy for managing climate risk, especially on major sources of CO_2 emission, power plants. There are different alternatives to mitigate CO_2 in the atmosphere, i.e., energy intensity

reduction, which needs the efficient use of energy and better energy management, reduction of carbon intensity which requires switching to use non-fossil fuels such as renewable energy and enhancing CO_2 sequestration that contains developing technologies to capture and mitigate more CO_2.

The strategies which can be utilized by the countries to manage energy better, and control greenhouse gases involve reduction consuming-energy services, increasing the efficiency of energy conversion or utilization, switching to lower carbon content fuels, enhancing the sinks for CO_2 and using energy sources with low CO_2 emissions, such as renewable energy. The options for enhancing CO_2 sequestration are sought to hasten to fix carbon in the biosphere and lithosphere, either by increasing natural sinking process to CO_2 fixations such as mineral carbonation, forestation and ocean fertilization or direct artificial CO_2 sequestration, i.e., injection into the ocean and geological formations. Although CCS (CO_2 capture and sequestration) is a relatively expensive mitigation option, it can be a midterm solution and an insurance policy to reduce environmental impacts and allows human continue to use fossil energy until renewable energy technologies mature [24].

Riahi et al. [25] studied a modeling of CO_2 capture and sequestration (CCS) incorporating factors of economic, demographic, energy demand and alternative policy. He concluded that CCS is one of the obvious priority candidates for long-term technology policies and protects human against the risks associated with high environmental impacts of climate changes. Iran is a member of OPEC (Organization of Petroleum Exporting Countries) that produces about 45% of the world oil and controls about 78% of the world oil reserves. Iran, the third-largest oil reserves in the world, by export of roughly 11% of world oil reserves (136 billion barrels) is one of the major exporters of energy. With around 19.7% of the world proven natural-gas reservoir, which are about 28,080 billion cubic meters, Iran has the second largest reservoir in the world [26,27]. Oil fields will most likely be the first large-scale geological targets due to their significant potential for storing CO_2 and benefits gained from more extracted oil [28].

Besides these major sources of energy, Iran has the second largest basin, the basin of Zagros, in the Middle East [29]. Stefan studied on screening and ranking of sedimentary basins for sequestration of CO_2 in geological media in response to climate change and found the basin of Zagros suitable for CCS [30]. Therefore, geological storage of carbon and enhanced oil recovery (EOR), increasing the extracted crude oil from an oil field, seems to be a suitable choice for carbon capture and storage. The extent to which each of these methods is used will depend on many factors, including available CO_2 sources and accessibility, the emission reduction targets, costs, environmental impact and, etc.

Deep saline aquifers, deep-seated coal beds, caverns and mines are the main geological storage alternatives. The outstanding barriers and challenges to deploy these formations are unknown geology and hydrogeology of the basin because of limited exploration, unattractive economics, public acceptance due to the risk arising from local catastrophic events, leaks and accidental release of large amounts of CO_2 back to the atmosphere such as Lake Nyos in Cameroon [31] and the absence of a comprehensive policy, legislation, and regulatory framework [32]. Nevertheless, saline aquifers for CO_2 geological storage is a technology that can be successfully and safely applied today as shown by the experience from active commercial storage projects at Sleipner, In Salah, Snøhvit, and acid-gas injection sites in Canada [33]. In a direct sequestration into the oil and gas reservoirs, CO_2 needs to be separated and captured from the flue gases of stationary sources before injection into reservoirs.

Thus, the CO_2 separation is the first and the most energy-intensive step of CCS. It has been accepted that CO_2 EOR projects have little major technical challenges, but there are economic constrictions if high-cost capture, transportation and injection of CO_2 are used for EOR and storage operations. CO_2 capture and transportation contribute roughly 75 percent to the overall CCS cost, and it increases the electricity production cost by 50 percent [34,35]. Besides the costs of CO_2 capture, compression, transportation and injection, the complexity of separating CO_2 from a gas stream will be too high making CO_2 EOR economically unattractive and reduced the interest in the CCS process in recent years.

Necessary criteria and characteristics of geological formations, oil and gas reservoirs for properly selecting an adequate CO_2 storage site are acceptable porosity, thickness, permeability, confining unit cap and, etc. Apart from them, other considerations must be made in CO_2 storage site selection such as location, accessibility and proximity to major CO_2 sources. Therefore, due to limited conditions such as scattered stationary sources, distant from oil and gas reservoirs or geological formation, high-cost capture, transportation and injection of CO_2 and complexity of separating CO_2 from a gas stream, other techniques need to be considered. Iran is the second greatest country in the Middle East and the 18th largest country in the world with a total land area more than 1.6 million km^2. If sufficient water is provided, one-third of Iran's total land area can be utilized for agriculture [36].

Geographically, Iran is located in the region that its climate ranges from arid or semiarid, to be subtropical along the Caspian coast. Because of different climates, vast land areas and the presence of various saline lakes, Iran has a natural advantage for algae culture. Saline lakes such as Lake Urmia, the third largest salt water lake on earth, can provide a wide and diverse range of microalgal species and more importantly the obvious possibility of establishing microalgae culture ponds [37]. These potentials make a chance for Iran to advance algae-based biofuel and carbon dioxide sequestration. Microalgae strains among the other plants are of particular interest because of their rapid growth rates and tolerance to varying environmental conditions [38–41].

Microalgae through the photosynthetic process can use CO_2 from the flue gases and convert it into O_2 and carbohydrates. Moreover, mass culture of microalgae could be as a source of commodities, including foods, feeds, fuels, and fertilizers, which can reduce capital and operating costs. Economic assessments and especially life cycle suggest the microalgal biofuels as one of the main biofuel products [42–45].

Therefore potentials and the possibility of achieving economic cultivation of microalgae for CO_2 sequestration and even high value products in Iran are highlighted due to large amounts of CO_2 sources, the presence of different saline lakes, unlimited access to saline water and sunshine for establishing microalgae culture ponds in different areas and string government support in the use of renewable energies.

Professor Yoichi Kaya of the University of Tokyo has summarized choices, which could reduce anthropogenic CO_2 emissions into the atmosphere and consequently, among them only three options remain. These alternatives included decreasing energy intensity, which needs the efficient use of energy, moderating carbon intensity, which requires switching to use non-fossil fuels such as hydrogen and renewable energy and enhancing the sequestration of CO_2, which involves developing technologies to capture and mitigate more CO_2 [46].

Therefore, this paper provides a status review of these options in capturing CO_2 from point source emissions in Iran. This review describes Iran's strategies in energy management in each sector for reducing greenhouse gases and investigates potentials of Iran for CCS and focuses on assessment of reduction of emissions from carbon sources by different methods such as CO_2 storage in geological formations, oil and gas reservoirs and microalgae biomitigation.

2. Mitigation strategies to control greenhouse gas emission in Iran

2.1. Energy management and control greenhouse gas emission by sector:

Due to location of Iran in a dry and arid region, it faces to shortage of water resources for drinking and agriculture. Since the increasing temperature causes negative effects in different sectors in Iran, some programs for GHGs emission reduction are established by the department of the environment (DOE) to force the energy sector to decrease GHGs emission about 30 percent. Currently, GHGs emission per GDP (kg equals CO_2 per GDP) index in Asia average (1.04 kg CO_2/2005 US$) and world average (0.59 kg CO_2/2005 US$) is lower than Iran (2.21 kg CO_2/2005 US$) [18,47].

Developed countries with investments in renewable energy, improving energy efficiency and new technology made giant strides in the energy sector have taken control of environmental pollution. Nonetheless, developing countries are facing serious challenges. Iran is a developing country with many natural sources of energies such as oil and gas. Iran owns the second-largest oil and gas reservoir in the world and the 4th greatest producer and exporter of oil in the world while it is the 4th greatest consumer of gas in the world. Furthermore, a strong dependency has been created between economic growth and the oil and gas during the hundred years of oil production and the forty years of development of gas consumption network [48].

The biggest provider of the government's budget and economic growth direct and indirect is oil revenue and affected by petrol-dollars. Oil export accounts for 80% of Iran's foreign-currency revenues and nearly 60% of the government budget revenue in 2010 which increase 10% in comparing to 2006 [49,50]. There are some weaknesses that affect the energy sector in Iran and cause more greenhouses gas production such as low energy prices due to subsidized energy in the domestic market, high-energy intensity, the existence of illogical and uneconomic relation in consumption because of low energy prices, a high amount of waste in various stages of oil and gas consumption since long ago, which has been continued to the present, high effectiveness of oil revenue in the economy and the impacts of oil revenue on investments in oil and gas productions.

The energy intensity value In Iran is higher than most industrial economies and even more densely populated developing countries such as China and India. Environmental average annual damage costs of air pollution from the energy sector in 2001 to be $4.7 billion (5.7% of nominal GDP) which is higher than the countries in the Middle East and North Africa Region [51]. Only the health costs of environmental damage of air pollution in 2001 is assessed about $7 billion, equivalent to 8.4% of nominal GDP and this damage cost in the money of 2001 will grow to $9 billion by 2019 which equivalent to 10.9% of nominal GDP. Energy in the domestic market is heavily subsidized.

It is estimated that if pricing policies to keep energy price constant continue to 2019, then subsidy to the sector will rise to (measured in Rials of 2001) 20% of GDP and consumption of energy and then the emission of greenhouse gases will be more than double [52].

Thus, serious policies and strategies should be implemented to have more efficient energy management. These policies can include improving the efficiency of production, refining and distribution of oil, gas, electricity and agriculture sector and introducing renewable energy such as wind, solar, geothermal energy and hydroelectric power. The strategies such as price reform, elimination of energy subsidies and substitution of fuel oil by environmental fuel, biofuels and natural gas, can keep damage costs in the future lower than the present [53–55].

Shafie-Pour et al. [52] studied the costs of environmental damage and concluded the strategy in elimination of energy subsidies in 2014 would reduce energy consumption by half from 1556 MBOE to 789 MBOE, and cause a 50% decrease of damage costs from 10.9% of GDP to 5.7% of GDP. Table 1 shows the share of greenhouse gases and emissions in each part of energy-consuming sectors in 2010.

2.1.1. Domestic and industry sectors:

When the electricity consumption rate grows faster than the rate of GDP, then it can be considered as an index of social and economic development in modernizing economies [56]. During recent two decades, the household electricity consumption rate has grown faster than the average GDP growth rate [57]. The population of Iran in 2011 reached 75 million with 1.29% annual rate between 2006 and 2011, and roughly two-thirds of the population were under the age of 30 [58]. The urban population accounts for 71.4% of the total population with a 1.9 % annual rate of urbanization. Thus, this urban growth of this population increases energy demand, and causes producing more greenhouse gases. In household, business and general sectors, all kinds of fuel are consumed such as solid, liquid and gas.

It is noticeable that this sector alone is the largest consumer of kerosene, about 97%. Household sector with a consuming 424.1 million barrel of equivalent crude oil and 40.6 % of total final energy consumption in 2010 is the largest consumer of energy in the country. Energy consumption growth in household, general and business sectors increased 23% relative to five years ago.

A coherent strategy must meet reducing the environmental costs of energy production and consumption while extending access to basic energy services in developing countries, and preserving energy security.

Therefore, this strategy will contain measures to increase the efficiency of existing energy sources, to reduce energy demand (through economic and other instruments), to progress renewable energy, and to transfer cleaner technologies to developing countries [59]. It has been proven that for reducing emissions of GHGs as much as 31% in 2021 the most economical alternative is enhancing energy efficiency. It would be possible to reduce the average annual growth rate of CO_2 emission from 4.2% to 2.4% in the period 1999–2021, only by the rational use of energy, which accompanied by changes in the fuel mix [58].

Enhancing energy-efficient option in the domestic sector includes defining better standards for energy consumption in household and commercial buildings, mandating the use of energy labels for household manufacturing of home appliances. Therefore, special attentions to the optimization of this sector can have favorable effects on energy savings, enhancing energy efficiency and reduction greenhouse gas emissions. Industry sector after domestic and transportation is the third major energy-consuming sector. The total final energy consumption in the industrial sector, with growth of 6.4% compared to the previous year, rose to 274.6

Table 1
Share of greenhouse gases and emissions in each part of energy consuming sector in 2010.

	NO_X	SO_2	SO_3	CO	SPM	CO_2	CH_4	N_2O
Domestic	6.6	7.0	8.6	0.9	1.8	25.0	7.3	4.2
Industry	9.3	22.2	32.1	0.4	2.8	16.6	4.1	2.6
Transportation	48.4	28.7	30.6	96.8	86.8	23.4	79.7	47.9
Agriculture	3.9	5.4	3.2	0.2	4.7	2.6	1.4	40.4
Refineries	N.A	N.A	N.A	N.A	N.A	3.2	0.7	0.4
Power plants	31.8	36.7	25.5	1.7	3.9	29.1	6.7	4.4

N.A: Values are not available.

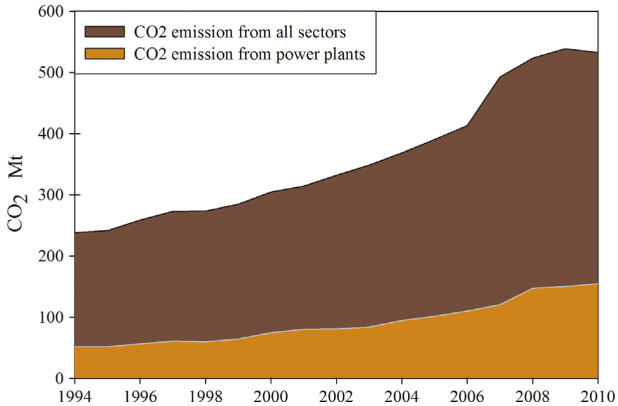

Fig. 1. CO_2 emission trend from all sectors and power plants in Iran during 1994–2010.

million barrels of equivalent crude oil. CO_2 emission factor in Iranian oil refineries is 3.5 times higher than European ones, like England. Therefore, in order to have a sustainable development in Iranian oil refineries, the government has to set emission factors of the European Community as its goal [60]. It is estimated that the potential of GHGs emission reduction in the oil sector, which major part of this is related to petrochemical complexes is about 67 million tons equal CO_2 in 2025 [61]. Petroleum refineries emitted close to one Gt CO_2 yearly worldwide, about 4% of global total emissions [62].

Since these industries are old and worn out, several effective techniques such as detection of energy losses and process problems could implement for their GHGs emission reductions. Therefore, the cost of tones of CO_2 reduction in the Iranian oil sector would be very lower than same industries with new technologies. Sekhavatjou et al. [63] studied naphtha hydrotreating unit of the Abadan oil refinery which, designed in 1960 and releases great amounts of air pollutants such as sulfur oxides and carbon dioxide into the atmosphere [64] and wastewater treatment plant and waste incineration furnace of the Tondgouyan petrochemical complex. Their results showed that in naphtha hydrotreating unit, the gas burning will reduce to 10.6 million kg annually by process changing once-through the system to recycle system.

Furthermore, about 1.75 million cubic meters will be saved by injection of producing methane (from anaerobic reactors of wastewater treatment plant) to waste incineration furnace due to prevention of gas sending to flare [61]. Apart from catastrophic greenhouse gas emission due to old industries, energy losses and process problem, Iran has planned to increase its refining capacity because of international energy sanctions. Hence, the necessity of comprehensive policies for GHGs reduction in Iranian oil industries appears more evident.

One of the other largest energy-consuming manufacturing and emission sector is iron and steel with nearly 20% of total industrial energy consumption and 30% of direct industrial CO_2 emissions, nearly 10% of global total CO_2 emissions in 2007 [65].

The second most CO_2 intensive industrial process, accounting for 2 $GtCO_2$/year worldwide in 2007, is cement production due to not only due to the large energy requirement, but also to the emissions from raw materials, 0.9–1.0 ton CO_2 per ton cement [66,67]. In these industries such as cement and iron and steel, energy-efficiency improvement and fuel switching have rate of capital return of 70% and 50% for cement and 134% and 182% of the iron and steel industries, respectively. In recent years, several measures have been taken by the organs associated with this section such as perform an energy audit, standards, criteria used and facilities to finance projects to optimize. For achieving energy sustainability in the country, Karbassi et al. [57] suggested measures in the following.

- Standardization of energy consumption in home appliances, industrial processes and transport fleets, residential and commercial buildings
- The establishment department of energy in all the industries and institutes with consumption of over 1 MW electricity or 1 million m^3 of gas to look into the possibilities of energy saving and also implement the measures
- Purchasing excess electricity produced by the Ministry of Energy at a tariff that will be set by the Government for any industrial sector or any institute generates electricity
- 25% discount on all energy-efficient equipment by the Ministry of Trade to encourage the use of such goods
- Importing energy recovery equipment along industrial, technological purchases
- Exempting manufactures from the 40 % tax by Ministry of Trade to promote the production of energy-efficient equipment within the country
- Encouraging Banks to pay 5% of their total loans by government to the energy-efficient measures
- Entitling any industry which saves energy to receive 50% of value of saved energy on an annual basis
- Establishing Higher Council of Energy in order to coordinate all energy affairs in the country, including energy conservation and renewable energy and, etc.

2.1.2. Transportation sector:

Iranian Fuel Conservation Company (IFCO), established in 2000, is one of the main institutions responsible for optimizing the energy consumption in the Ministry of Oil. Its main task is the management of energy optimization in the transportation sector, which is one of the major energy-consuming sectors.

The main consumer of gasoline is the transportation sector. Among petroleum products, gasoline has had the maximum annual growth rate by 9.07% during 1997–2006 in Iran [68]. Transportation sector with a consuming 299.7 million barrel of equivalent crude oil in 2010 is the second energy-consuming sector, which 55.8% of total final consumption of petroleum products is allocated to own and has growth of 10.2% compared to five years ago. In according to Table 1, transportation sector with 48.4% NO_X, 96.8% CO, 47.9% N_2O, 79.7 % CH_4 and 86.8% SPM has the highest share in the release of various gases in the sectors of energy consumption in the country. A review of historical trends of gasoline sale and import prices in Iran show that the most important factor affecting the uncontrollable gasoline consumption growth is low prices of gasoline. Moreover, the rise in automobile mass production due to expanding the production of spark ignition vehicles plays an increasingly important role in Iran's concern for gasoline consumption in the recent years [69]. Besides the rise in automobile mass production with average annual rates of 20% between 1999 and 2010, the number of motorcycles which are manufactured based on the 1970s technology in Iran has increased considerably over the last 10 years and reached 10.4 million at the end of 2009 with a growth rate of 4.3% relative to the previous year.

Unfortunately, low levels of technologies are applied in domestic producing automobiles such as the engine technology of the 1980s in nine different car models, which comprised 24.2% of domestic produced vehicles of 2006 and the technology of the 1970s in six different vehicle models, which comprised 40.9% of the domestically produced vehicles in 2006 [69,70]. Apart from low levels of technologies used, 25.6% of motorcars had the

average age of 6–10 years old and 38.1% of trucks and tractors had the average age more than 30 years old at the end of 2009, is another concern in Iran's transportation system. If the ownership level in Iran, 160 (vehicles/1000 persons) at the end of 2009, wants to reach the ownership levels of developing countries such as the US and Canada with 828 and 620 (vehicles/1000 persons) respectively, the crisis of fuel consumption and air pollution will increase dramatically. In 2000, in the capital of Iran, Tehran, the index of air pollution, Pollutant Standard Index (PSI) 24, reported 282 "unhealthy" days and on January 2, 2005, it reached 168, close to "very unhealthy" levels which by on the same day; PSI in New York and Bangkok was 52 and 57, respectively. That air pollution caused schools were closed and children, the elderly and the sick were advised to stay indoors. [71] In accord to air pollution of SPM, Tehran in 2009 had 20 unhealthy days, one very unhealthy day and one dangerous day. Apart from of Tehran, another six mega cities in Iran are no different to Tehran. For example, in accord to air pollution of SO_2, Shiraz had 188 unhealthy days and 70 alert days in 2009. Furthermore, the growth in Iran's population is greatly causing an increasing number of cars and automobile exhaust [72,73]. In order to manage energy and reduce emissions in the transportation sector, various policies and strategies are provided which most important measures are based on at first enhancing autonomous vehicle efficiency, technical progress for conventional and alternative vehicle propulsion technologies and modernizing the cars, then improving methods of transportation, quality of fuels, developing criteria, standards and audit of fuel consumption.

It is estimated with Implementation of approved standards, during the period 2008–2012, about 6.6 and 2.3 million liters per day of gasoline and diesel consumption will be saved. The conclusion of a research in the transportation sector of six developing countries, namely Turkey, Thailand, Pakistan, Morocco, Tunisia and Malaysia indicated that the pricing policies of oil products in the transportation sector have a crucial role in shaping rational economic and energy strategies within the framework of rising environmental concerns [74]. In the absence of price reform and control policies, it is estimated that health damage in Iran will grow to $8.4 billion in the transport sector [52].

The main challenges from the point of view of Aghaii Tabrizi, the former managing director of National Iranian Oil Refining and Distribution Company (NIORDC), are unusual traffic conditions, air pollution, undefined relations between development and welfare, the nonintegrated relationship between vehicle production and gasoline production and absence of investment by the private sector in making petroleum products. In addition, the major solutions are introduced organizing, planning and managing the demand and consumption of gasoline [75,76].

2.1.3. Power plant sector:

Since that economic growth in Iran depends on electricity, therefore, the country has to build many new power plants to keep the trend of electricity generation and guarantee this growth. The growth of electricity consumption in Iran was eleven times within the last 30 years, which nominal capacity has increased by 1552 MW annually and reached to 61454 MW in 2010 and chose to emit about 154.8 M ton of CO_2. Nominal capacity in 2010 increased 49.7% and 8.8% compared to 2004 and previous year. With these increases in electricity generation and nominal capacity, Iran has been ranked 19 in electricity generation in the world in 2009 [27,77]. Among fossil-fueled power plants, coal-fired plants being the main CO_2 contributor and all fossil-fueled power plants are responsible for about 30–40 percent of total CO_2 emissions [78,79]. Six types of power plants in Iran, which generate most electricity are the gas turbines, steam turbines, combined cycles and hydro powers and less than 1% by diesel engines and only 0.1% using the renewable wind energy. Air pollution emissions from thermal types are more than other types. Although hydro power plants have 13.8% of nominal capacity, but roughly 96% of electricity produced is from fossil fuel based power generators in 2010. Due to the water shortage in the country, only about 3.3% of the electricity is generated by hydro power plants. Fig. 1 shows the emission trend of CO_2 in all sectors and power plants from 1994 to 2010.

During last two decades, 1989 to 2010, natural gas has been used in combined cycle power plants compare to other thermal types, because of enormous gas resources in the country and its less emission. Therefore, the share of both gas turbine and combined cycle together has been increased from 25% to 60%, while the share of the steam power plants decreased from 56% to 25.6%. Fuel oil, diesel and natural gas are the fuel types in thermal power generators in Iran. The share of gas, fuel oil and diesel in electricity generation in Iran was 74.2 %, 15.8% and 9.7% in 2010, respectively.

Depending on fuel availability over the year in the country, more than one fuel type is used in the power plants. Due to the increase in residential natural gas consumption in later years in the winter and the drop gas pressure and the resulting disruption in the supply of gas for power plants, growth in consumption of liquid fuels in power plants in recent years has been seen. Thus that the consumption of liquid fuels in power plants of the average of 2005 to 2010 for fuel oil and diesel increases 7% and 11.5%, respectively. However, natural gas consumption during the same period grew by only 2.6 percent yearly. As shown in Table 1, it is noticeable that power plants and transportation sectors have the highest share in the release of SO_2, while power plants and domestic and industrial sector have the utmost share in the release of CO_2 in this year. The share of greenhouse gases and emissions in each part of energy-consuming sectors from the point of types of major fuels consumed in 2010 are presented in Table 2.

Natural gas compared with other fossil fuels, is a clean fuel and has the least amount of pollution. However, as shown in the previous table, 54% of total carbon dioxide emissions in the energy sector relate to natural gas, which is very noticeable to the issue of

Table 2
Share of greenhouse gases and emissions from the point of types of fuels consumed in 2010.

Fuel	NO_X	SO_2	CO	SPM	CO_2	CH_4	N_2O
LPG	0.1	0.002	0.2	N.A	1.4	1.3	0.3
Gasoline	16.7	2.5	95.5	4.4	10.0	47.9	20.3
Kerosene	0.1	0.9	0.05	N.A	2.5	1.1	0.9
Diesel	40.9	39.0	2.0	46.3	18.6	9.1	68.7
Fuel Oil	8.1	55.8	0.6	42.1	10.8	3.8	3.3
Natural Gas	31.8	0.04	1.3	4.3	54.0	34.6	4.4
Coal	N.A	N.A	N.A	N.A	0.01	0.001	0.01
Others	2.3	1.758	0.35	2.9	2.69	2.199	2.09

N.A: Values are not available.

Table 3
Electricity loss in transmission and distribution lines.

Year	Distribution (%)	Transmission and Sub-Transmission (%)
2000	11.0	5.1
2005	18.1	4.2
2006	18.0	4.3
2007	17.9	4.9
2008	17.5	4.2
2009	16.1	4.1
2010	14.8	3.6

climate change. Economic development and use of renewable-energy production systems, the development of hydroelectricity capacity with significant hydropower potential and the replacement of fossil fuels consumed in the country are Executive's policies. The share of wind power, solar and biogas power plant with total installed capacity of power plants was only 0.15% in 2010. Mashhad biogas power plant with nominal capacity 660 kW, Shiraz biogas power plant with nominal capacity 1200 kW, Tabriz solar power plant with nominal capacity 24 kW and Tabriz wind power plant with nominal capacity 660 kW are examples of renewable power plants, which were constructed in recent years but their shares in supplying energy are nil.

The average efficiency of power plants in Iran is 36.8%, which 0.3% and 9% have been increased compared to previous years and past 30 years, respectively. The efficiency of thermal, gas and combined-cycle power plant was 36.6, 29.4 and 44.7 percent in 2010, respectively [80]. Various policies and strategies in order to manage energy, increase efficiency and reduce emissions in the power plants sector will be done such as combined cycle power generation, carry out energy audit in power plants, establishment of an energy management, cooling of the inlet air gas turbine, condition monitoring of fuel consumption and research about reduction of domestic consumption of power plants.

Additionally, another policy which done in Iranian power plant was switching from liquid fuels like diesel or fuel oil to natural gas that the amount of CO_2 emission from thermal power plants has reduced to 83 million tons in 2005 in comparison to 89.4 million tons in 2000, a decline of 7.2% [73]. It is estimated that change in the structure of power industries will increase consumption of natural gas by 47% and diesel by 50% before 2025, and CO_2 emission will increase 1.6 times for the new power plant composition. Whereas if the structure of the power industries does not change, and the old composition continues in the future, fuel consumption will increase by 130%, 106% and 69% for natural gas, diesel and fuel oil respectively and CO_2 emission will increase another 2.1 times for older power plants [81].

Some studies investigated that the high growth rate of energy consumption was because of over US$ 50 billion subsidies in all energy sectors, including electricity sector and about 22% electricity loss in transmission and distribution [57,77,82]. The electricity loss of transmission and distribution is tabulated in Table 3 and show a rise in each year compare to the previous year, which imply that the energy sector in Iran is unsustainable, and the country faces many problems in the energy sector [83].

Due to the multiplicity of alternative technologies and fuels available for the power plant sector, both economic and environmental measures should be considered for comprehensive and optimized structure in the electricity generation of the country [84].

Many studies have been conducted to mitigate emissions in this sector, such as Holttinen that investigated the effect of wind energy on CO_2 abatement in the Nordic countries. Another study by using renewable energy in Vietnam decreases the cumulative emission of CO_2 by 8%, SO_2 by 3%, and NOx by 4% [85,86]. In addition, Romeo showed that in Spain with carbon capture and storage (CCS) and renewable energies can reduce CO_2 emission up to 90% by 2050 and in order to maintain economic development without increasing CO_2 emissions as an active response to Kyoto protocol targets is necessary to the development of CCS projects in Spain [87].

2.2. *Clean and renewable energies:*

Currently, nonrenewable sources such as natural gas, fuel oil and diesel are used in most of Iranian power plants to generate electricity. Mazandarani et al. [81] shows a clear view of 42 years an evolutionary trend of Iran's electricity generation industry and concludes that encouraging of using renewable-energy sources besides of increasing combined cycle and using more natural gas is recommended to reduce emissions. In consideration to major resources of fossil energy in most Middle East countries, the use of renewable-energy sources has started to be an interesting issue for scientific communities and governments [88].

It is predicted by the Energy Information Administration (EIA) that renewable energies are projected to account for a modest 3% of the Middle East total electricity generation by 2030 [89]. Since that most different types of renewable-energy sources are available, it is possible to be implemented them for gaining required energy supply [90]. Based on the scheming in the 4th Socio-economic and Cultural Development Plan (2005–2010), the private sector is expected to have a share of at least 270 MW in renewable energies [91]. In Iran, nominal electricity generation capacity of the country from the renewable sources of energy, including wind, solar and geothermal will account for 3% [92]. In the following, the potentials of main renewable energies in Iran are described.

2.2.1. *Wind energy potential:*

From wind energy by using wind turbines can generate electricity. The wind energy like the other sources of renewable energy is widely available but scattered. Due to no need to use fuel and water, reduction of electricity production costs, employment, development of environmental attitudes and, etc., the use of wind energy in comparison with other sources of renewable energies could be a good choice. Iran has a good potential for extending wind turbines and producing electricity using wing energy. It is initially estimated to have total potential 30,000 MW from wind power [81,93]. During the 4th Socioeconomic and Cultural Development Plan, installed capacity of wind power plants with growth of 90% from 47.6 MW in 2005 has reached to 90.6 MW in 2009, and capacity of wind power has growth of 2460 kW in 2010. Based on the next Development Plan, 2500 MW of wind turbines will be installed [80,94].

Manjil wind power plant with 60.6 MW and Binalood wind power plant with 28.4 MW are major projects in the field of wind energy. So far, the investigations and the research projects, estimate the wind potentials include 45 sites and 26 regions in Iran.

2.2.2. *Solar energy potential:*

Solar radiation on Earth as the largest renewable source is one of the clean-energy sources, inexpensive and free of harmful environmental effects. In general, solar-energy systems utilize as new technologies in the provision of lighting, electricity, hot water, heating and cooling air, ovens and water desalinations. The average solar radiation for Iran is about 5.3 kWh/m2/day and it is even higher in the central region of Iran, with more than 7.7 h/day (more than 2800 h/year) [95,96]. The projects to be completed during the 4th Socioeconomic and Cultural Development Plan are an off-grid photos voltaic (PV) systems and solar water heaters. Due to average solar radiation about 5.3 kWh/m2/day and even higher in the central region in Iran with more than 7.7 h/day (more than 2800 h/year), Iran has much potential to design and manufacture solar systems. This potential persuades Ministry of Energy to support and install the first 250 kW pilot solar thermal power plant in Shiraz [82,97]. Furthermore, the first and biggest solar power plants, integrated solar combined-cycle system (ISCC), in the Middle East is under construction in Yazd. Economic and technical assessment indicates that it is the most suitable renewable-energy project in Iran [98].

2.2.3. *Geothermal power potential:*

Geothermal energy is the energy released as heat within the Earth's crust, which usually in the form of hot water or steam and

at sites with suitable conditions for this type of energy to generate electricity or direct application are used for heating the region, agriculture, etc. The North and North West of Iran have a substantial potential for geothermal energy. Approximately, 8.8% of Iran, about 18 fields, prospects for geothermal power plant potential areas [99]. It is estimated that internal geothermal energy provides about 1400 MW of power to the consumers in Iran [100]. Company (ENEL) recommended that Sehand, Sabalan (Booshli), Damavand, Sarein and Maku–Khoy regions have promising prospects for electrical generation by geothermal energy. Additionally, the Center of Renewable-Energy Research and Application (CRERA) -AEOI, and Ministry of Energy approved 10 more potentially suitable regions for this purpose in other parts of Iran [101]. Now the major project of the Department of Energy in this field is Meshkin Shahr geothermal power plant with installed capacity 200 MW [82]. In addition to the cases mentioned above, in the field of fuel cell, biomass, biogas and hydrogen, there are also projects that are already in the running in Iran.

Some of these projects are construction of biogas plants in both Shiraz with 7455 MW and in Mashhad with 4875 MW in 2009, purchase, installation and commissioning of a water electrolysis system 30 normal cubic meters per hour.

3. Carbon capture and sequestration:

However, several options have been suggested in order to mitigate CO_2 emissions into the atmosphere such as reducing energy consumption, enhancing the energy conversion efficiency, switching to low carbon intensive fuels and using renewable energies. These options in comparison to CO_2 global growth may not be enough to mitigate global warming in the future. Therefore, another technology should have been chosen to provide a medium-term solution to mitigate environment impacts. CO_2 capture and storage or utilization has been projected as a potential solution to minimize the emissions which can bridge the gap to a sustainable future, based on renewable and more efficient use of energy [101–103]. Successful implementation of CO_2 capture and storage for minimizing the emissions of CO_2 from power plants, industries and other large CO_2 emission point sources depend on the establishment of cost efficient CO_2 separation, capture, compression, transportation and finally, the safe and permanent storage of the gas in suitable mediums. Suitable techniques for separating CO_2 from a gas stream which involves scrubbing the gas stream with a chemical solvent were developed 60 years ago [104]. Recently, besides of separation methods, several thousand installations have been developed. For example, only Kohl and Nielsen mentioned 334 of them, which using a physical solvent scrubbing. Processes of CO_2 capture and sequestration (CCS) contain a capture process which includes Oxy-fuel combustion [105], pre combustion, post combustion process as well as chemical looping combustion [106,107], transport, process and storage, which can be done by deep geological sequestration, mineral carbonation, or ocean storage. For CO_2 storage, there are many options, which involve the injection into deep water [108,109], geological formations such as oil and natural gas reservoirs [110,111], saline formations [110–115] and unminable coal seams [116]. It is obvious that for purposes of managing storage sites and verifying the extent of CO_2 emission reduction, which has been achieved, monitoring will be required. Seismic, gravity survey technique has developed by the oil and gas industry for observing CO_2 underground [112,117–119]. Among the capture, transport and storage processes, CO_2 capture and transport are cost and energy intensive and CO_2 capture due to more technically challenging has attracted the most attention in the literature. Instead of CO_2 storage, several applications and utilization of CO_2 have been proposed: for example, using CO_2 to make chemicals or other products such as the synthesis of cyclic carbonate via cycloaddition of CO_2 to epoxide, [120] propylene carbonates (PC), [121] CO_2 reforming of CH4, [34] reaction of CO_2 with ethane and propane for producing ethylene and propylene, [122] CO_2 hydrogenation to methanol, [123] synthesis of dimethyl carbonate from CO_2 and methanol, [124] and refrigeration and food preserving, gaseous soft drinks, antibacterial and antifungal agent, firefighting, foaming agent, fixing CO_2 in mineral carbonates for storage in a solid form, storing it as solid CO_2 ('dry ice').

Clearly rate of CO_2 emissions is very higher than these various applications, utilization and all of CO_2 demands. Therefore, necessary plans for reduction, capturing and storing of CO_2 must be done as soon as possible. Iran is the first in the contribution of CO_2 in the Middle East and 9th in the world, and CO_2 has few applicants in its industries. To address this, due to natural potentials Iran could apply a range of technical research and development projects of CCS. In the following, different methods for utilizing these potentials in Iran are described. Before it, sources of CO_2 in Iran are mentioned.

3.1. CO_2 Sources for capture in Iran

For the reduction of CO_2, the best methods are carried out at large-point sources of emissions, such as power stations, which currently account for about a third of global CO_2 emissions. Other large point sources include petrochemical, oil refineries, gas processing plants and fertilizer, steel works and pulp and paper mills. In this article we will concentrate on large-scale power generation, but many of the other points industries might also be major sources of emissions.

3.1.1. Combustion Sources

The industries that operate by using fossil fuels as sources of energy are grouped in here. The main parts of these industries are power plants, petroleum refineries, cement industry, steel and iron industry and petrochemical industry. 5–15% of the flue gas of these industries is CO_2, depending upon the type of fuels. Therefore, in some methods of CO_2 capturing, which needs to purify CO_2 from other elements, the costs are high. Among these industries, power plants are major sources of CO_2 in Iran. Fig. 2 shows the share of CO_2 from different sectors within the country in 2010. According to this figure, over 154.8 Mt CO_2 per annum, 29.1%, are emitted from power plants. In 2010, 52.7% of CO_2 emissions from Iranian power plants were produced from thermal power plants, 25.5% from combined cycle, 21.7 % for gas and 0.1 of diesel power plants.

3.1.2. Non-Combustion sources

The important part of this group is natural-gas processing plants which CO_2 and H_2S (Acid Gases) are the products from these plants. Iran possesses one of the world's greatest non-associated gas fields,

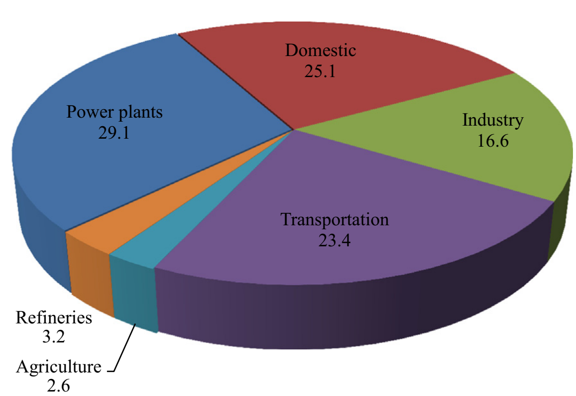

Fig. 2. The share CO_2 emission of different sectors of the country in 2010.

Table 4
Amount of flare, vent and burned acid gas of some Iranian gas refineries in a period of 2004 until 2010. Mm^3/day (million cubic meters per day).

Gas Refinery	Flare, Vent & Burned acid gas (MM m^3/day)	2004	2005	2006	2007	2008	2009	2010
Fajr	Burned acid gas	589.6	556.6	553.6	519/0	559.0	551.0	561.73
Khangiran	Vent gas	195.1	286.2	293.8	303.1	320.4	329.2	99.7
Bid Boland	Burned acid gas	54.2	42.8	32.1	33.6	46.9	47.6	76.9
	Flare gas	46.4	40.2	38.2	40.0	36.6	30.7	43.6
Masjed Soleyman	Burned acid gas	N.A	N.A	N.A	N.A	0.1	0.1	0.2
	Flare & vent gas	N.A	N.A	N.A	N.A	0.1	0.1	1
Sarkhon o Gheshm	Burned acid gas	N.A	20.2	N.A	N.A	N.A	N.A	N.A
	Flare & vent gas	N.A	N.A	N.A	N.A	N.A	21.2	20.0
South Pars phase 1	Burned acid gas	N.A	14.1	77.9	89.9	103.2	131.6	101.0
	Flare gas	N.A	3.6	88.4	102.8	116.9	156.1	133.0
South Pars phase 2 and 3	Burned acid gas	8.6	10.2	222.2	276.7	298.5	301.1	277.9
	Flare & vent gas	163.5	128.9	269.1	316.3	332.1	337.5	301.3
South Pars phase 4 and 5	Burned acid gas	N.A	N.A	229.9	281.9	307.7	302.2	197.8
	Flare & vent gas	N.A	N.A	343.5	322.2	344.3	337.1	173.8
Parsian	Flare & vent gas	N.A	30.8	107.1	321.8	285.7	167.7	44.6

N.A: Values are not available.

has the world's second greatest reserves after Russia, and natural-gas production in Iran will reach 900 million m^3 per day by 2015 [125]. Refining capacity of natural gas during 2005 to 2010 of 383 million cubic meters daily, with an annual growth rate about 6.2 percent is reached to 518.5 million m^3. Acid gas is natural gas or any other gas mixture, which contains significant amounts of hydrogen sulfide (H_2S), carbon dioxide (CO_2), or a mixture of them. Acid gases are treated in sulfur recovery units under normal operation of gas processing plants. If the natural gas has a high concentration of H_2S, sulfur recovery is the main part of gas processing plants. Due to pure CO_2 after sulfur recovery in these units, the cost of CO_2 capturing is low. An extensive inventory of these CO_2 sources were available in the south of Iran due to the major gas field, South Pars. Natural-gas processing in the southern region of Iran emits approximately 1 Mt of high-purity CO_2 per annum (more than 96%) [126].

In Iran, major amounts of natural gases and acid gases are burned due to being an excess of capacity of sulfur recovery units and not enough necessary measures for processing. In some case, it is not economical or practical to process because of small volumes of gases. In these situations, several options for disposing of unmarketable natural gas include flaring, incineration or venting is underground injection or using methods such as pipeline heating and electrical generation. Injection of acid gases not only disposes of H_2S safely; it also reduces greenhouse-gas emissions of CO_2. Besides environmental impacts of these gases, they cause dangerous diseases such as cancer [127]. In some regions, natural gases are flared or even vented to atmosphere. Venting these gases releases methane, which has 23 times as much global warming potential (per ton) as carbon dioxide. Shafie Pour et al. [52] evaluated the damage cost from the flaring of natural gas to the global environment on the basis on a carbon price of $10/ton CO_2 to be approximately $600 million per year, which is equal to a little less than 1% of current GDP in Iran. Besides acid gas flaring, associated gases, as a by-product of oil separation, are also flared when their volumes exceed the requirements. According to the official data and satellite data, Persian Gulf is one of the regions which the most wide-scale associated gas flared and Iran in this region is number one. The actual volumes of associated gas flaring in Iran are relatively difficult to estimate.

Until recently, after Nigeria and Russia, Iran is the highest flaring countries in the world. Iran with 11.4×10^9 cubic meters annually, accounts for 8.1 percent of the flaring and is the third-leading contributor to world gas flaring at the end of 2011. This is roughly equivalent to 2% of natural-gas consumption by the European Union countries, 1.7% of US consumption or 5% of Russian gas exports [128]. Despite this volume of flaring, Iran is not a member of Global Gas Flaring Reduction (GGFR) Partnership, which is established by the World Bank in 2002 to minimize worldwide flaring.

It shows that Iran lacks efficient, effective regulations on flaring and venting. Therefore, effective enforcement of regulations to approve flaring and venting permits, monitor flaring and venting volumes, and implement operational standards are crucial to reducing flaring. The National Iranian South Oil Company started Amak project in February 2005 to prevent flaring of seven Mm^3 per day of sour gas from one of the carbonate reservoirs in the Ahwaz oil field in south of Iran [129]. Acid gas injection technology in geological formations is relatively new topic, and for the first time in 1989 on a depleted reservoir oil (Blaimore field) had done by Chevron Company and after it, in 1994 in a layer of salty water in Canada. Since 1990, about 45 plants in Alberta and British Columbia have adopted to inject acid gas [130]. On the other hand in Iran, until now, there is not any plan for acid gas injection. Table 4 shows amount of flaring, venting gases from some Iranian gas refineries and also acid gases, which burned in the period of 2004 until 2010. Because of growing gas production, the amount of flaring, venting and burning acid gas was increasing. In according to this table necessary measures as soon as possible should be done for them. Large volume of acid gas as a critical factor threatening environment produced in North and South Pars and requires management and control. Acid gas injection into geological formations can be a good strategy to protect human health and the environment, reduction of greenhouse-gas carbon dioxide and high costs of desulfurization in the region [131].

3.2. CO_2 capture:

An essential part during the CO_2 sequestration process in the carbon management, which contributes 75% to the overall CCS cost is capturing CO_2 from flue gas streams and can be performed by three systems: post-combustion, pre-combustion and Oxy-fuel combustion [39]. The important factors in choosing the capture system are the gas stream pressure, the concentration of CO_2 in the gas stream and the fuel type (solid or gas) [132]. Post

combustion, pre combustion and Oxy-fuel combustion is basic options for the capture of CO_2. Post combustion contains removing CO_2 from flue gases, which CO_2 is only a small part of it after hydrocarbon combustion and emitted to the atmosphere after hydrocarbon combustion. The main parts of flue gas are nitrogen, oxygen and water vapor.

Due to presence of other gases in flue gases, which cause insufficient storage space and too much energy would be needed to compress them; some methods of separation are needed to capture the CO_2 in a post combustion process. The low concentration of CO_2 in flue gas causes a large volume of gas has to be handled. Therefore, large and expensive equipment, requirements of powerful solvents to capture CO_2 and regeneration of these solvents which require a large amount of energy are disadvantages of this process. For increasing the amount of CO_2 in the flue gases, using concentrated oxygen instead of air in burning fuel, which called the process Oxy-fuel combustion process was recommended. Reduction of flue gas volume due to the absence of nitrogen component of air, which causes reduced fuel consumption, energy and the size of equipment are advantages. On the other hand, being expensive of oxygen production and separating it from the air, both in terms of capital cost and energy consumption is its disadvantage.

Despite this cost, the results suggest that Oxy-fuel combustion capture for furnaces and heaters compared to post combustion capture using amine solvent can achieve a 48 % reduction in CO_2 avoidance cost [133]. Kuramochi et al. [134] reported that the economic performances of amine-based capture from the flue gas and Oxy-fuel combustion capture for refinery heaters were very similar. In pre-combustion capture, through a process which is known as gasification, partial oxidation or reforming, a mixture of carbon monoxide and hydrogen are produced by reaction of fuel with oxygen or air and in some cases steam. Then this mixture is passed through a catalytic reactor, called a shift converter, where CO_2 and more H_2 are produced by the reaction of CO with steam. After this step, the CO_2 is separated and the H_2 is used as carbonless fuel, and it is the profit of pre-combustion capture. During pre combustion capture, the equipment is much smaller and different solvents can be used, with lower energy penalties for regeneration due to higher CO_2 concentration and pressure. The high total capital cost of the generating facility is the disadvantage of pre-combustion capture [135]. Presently almost all commercial processes for capturing CO_2 still use liquid alkaline solutions, and amine scrubbing has been widely used on a large scale across several industries and well known technology for capturing CO_2 from flue gas [136–140]. Monoethanol amine (MEA) is the industries are most important and well-studied amine-based scrubbing solvent [141].

However, Ionic liquids due to many unique properties in comparison to other solvents such as extremely low volatility, the broad range of liquid temperature, high thermal and chemical stability have been considered as a potential substitute of aqueous amine solutions for CO_2 capture [142–145]. Owing to the disadvantage of liquid sorbent such as corrosion, many researchers have investigated and studied CO_2 chemical adsorption using dry regenerable solid sorbents, which can be divided into an amine-based such as solid amine sorbents relying on supports like silica gels, activated carbon, and SBA-15 [146–148] and alkali metal-based sorbent such as CaO [149,150] and alkali metal carbonate such as K_2CO_3 on various supports, including activated carbon, MgO, ZrO_2, SiO_2, Al_2O_3, TiO_2, CaO, and zeolites [151].

A fluidized bed in a solid CO_2 absorption process which can control high volumes of flue gases and heat to prevent hot spots generated during the exothermic carbonation reaction is proposed as a proper process [152].

Yang et al. [78] proposed various technologies for CO_2 separation such as absorption, adsorption, membrane separation and even new concepts such as chemical looping combustion and hydrate based separation thoroughly discussed. CO_2 capture technologies with regard to a timeframe can be categorized into short midterm future technologies, which likely be commercialized in 10–15 years. All required components in these technologies are commercially available and long-term future technologies, which are considered either in modeling or the laboratory phase today and likely be commercialized in 20 years or more [153].

3.2.1. Cement industry:

For the cement industry, literature seems to agree that post combustion capture appears to be the only commercial technology with a low-risk, and that enables retrofitting in the short midterm [154,155]. Nevertheless, in the long term for new plants, Oxy-fuel CO2 capture from the entire cement plant is likely to be available. Oxy-fuel combustion in comparison to post combustion requires rebuilding most of the core units within the cement plant. However, a significant economic advantage of Oxy-fuel CO2 capture over post combustion capture even with a major rebuilding of the kiln leads to undertake the Oxy-fuel combustion retrofitted rather than implementing post combustion capture. In the long term, the only option for post combustion CO2 capture for competing with technology of Oxy-fuel combustion capture, both in terms of CO2 avoidance rate and CO2 avoidance cost is using advanced solvents. Post combustion capture using MEA with probable future of CO2 price range (30–75 €/ton) is unlikely to become economically feasible unless low cost steam is available [155]. In post combustion utilizing chemical absorption capture, process integration and the use of waste heat or low-grade industrial heat is crucial to its economical operation.

3.2.2. Petroleum refineries and petrochemical industry:

As with the cement industry, post combustion capture using chemical absorption is considered to be the only feasible option in the short midterm in petroleum refineries and petrochemical industry for both steam-cracker furnace gas and refinery stack gases due to the low partial pressure of CO_2. Despite this, Kuramochi et al. suggested that for short midterm future, Oxy-fuel CO_2 capture (50–60 €/tCO_2 be avoided) is more economical than post combustion capture ($>$70 €/tCO_2 be avoided). It should mention that their result largely dependent on the economic evaluation of the consumed steam for both combined heaters and furnaces of two Mt CO_2/year scale and catalytic crackers of one Mt CO_2/year scale.

For post combustion in petroleum refineries and petrochemical industry with only using the state-of-the-art solvents and other advanced solvents currently under development can bring down capture costs. However, for the longer term, Oxy-fuel CO_2 capture with an integrated air separation unit and combined heat and power plant may become most economical [134].

The feasibility study on the oxyfiring fluid catalytic cracker, which, assuming an account for 16% of total refinery CO_2 emissions results significantly lower CO_2 capture costs compared to post-combustion capture [156,157]. For iron and steel industry, some advanced CO_2 capture technologies such as top gas recycling blast-furnace or smelting reduction may lead to more energy-efficient industrial production [134]. An alternative method to increase the CO_2 concentration in the flue gases is to use pre combustion process, which involves reaction of fuel with oxygen and/or steam to give mainly carbon monoxide and hydrogen. In contrast to Oxy-fuel combustion, pre combustion CO_2 capture due to utilizing nearly pure hydrogen does not require any modification of steam boilers and fired furnaces and is also likely to become technically feasible in the short medium-term. Nevertheless, pre combustion

capture does not seem economically promising with regard to probable future of CO_2 price range (30–75 €/tonne) [158].

3.2.3. Power station:

Since fossil-fuel burning power plants have the highest density of CO_2 emissions in terms of mass per power output and account for about a third of global CO_2 emissions, [24] they provide an appropriate target in the attempt to mitigate the global warming. Natural-gas combined cycles, pulverized coal-fired steam cycles and integrated gasification combined cycle (IGCC) are the main technologies used to generate power from fossil fuels. For the traditional pulverized coal power plants, the post combustion process is more suitable for CO_2 capture [159–161]. Application of Oxy-fuel technology seems more efficient than amine scrubbing, but in some cases due to new design and development such as natural gas combined cycle plants, which need specific gas turbine, Oxy-fuel technology is more difficult to implement. While in other cases such as a steam cycle power plant does not have this problem and by the help of recycling a fraction of flue gas into a combustion chamber to reduce the flame temperature, an ordinary boiler can easily be turned to an Oxy-fuel boiler [162].

A number of studies have investigated methods of CO_2 capture and evaluated CO_2 capture and sequestration costs in different power plants based on technologies that is either commercial or under development [163–165]. Khorshidi et al. [162] evaluated an amine based system for post combustion of CO2 capture, which injected into a deep saline aquifer or used for enhanced oil recovery for pulverized coal, natural-gas combined-cycle plants and the integrated gasification combined cycle plant. They resulted that the integrated gasification combined cycle plant is the lowest-cost system for all cases. However, with aquifer storage, the pulverized coal plant has the highest; while the natural gas combined cycle plant has much cost of electricity for EOR than the others.

It should be mentioned that due to the diversity in operating conditions and the type of products generated, the economic performance of CO_2 capture technologies will depend largely on individual plants. Since CO_2 capture from industrial processes increases significantly the electricity exports to the grid, the overall CO_2 capture performance may depend largely on the conditions of the local power market.

3.3. CO_2 storage:

To choose an effective method of CO_2 storage, it needs to have a low environmental impact, low-cost and conform to national and international laws and also the CO_2 must be stored for several hundreds or thousands of years. The main option for storing CO_2 are geological formations such as oil and gas reservoirs, deep saline reservoirs and unminable coal seams or ocean beds [166,167]. CO_2 is injected for storage at depths greater than 1000 m into sedimentary formations by utilizing technology derived from oil and gas industry [168]. In the following, the main methods for storage of CO_2 in Iran are mentioned.

3.3.1. CO_2 Storage in Ocean Beds:

A potential way for CO_2 storage is a direct injection of CO_2 in ocean depths where it will be dissolved or form hydrates or heavier-than-water plumes that will sink into the bottom in the ocean [169]. In accord to atmospheric CO_2 stabilization concentration, oceanic storage capacity of CO_2 can be defined. Thus, regardless of whether releasing of CO_2 to the ocean or air can occur, with atmospheric CO_2 stabilization concentrations ranging from 350 ppm to 1000 ppm, roughly 2300–10,700 Gt CO_2 in equilibrium with that concentration would be stored in the ocean [163,170,171]. Xu and Hill et al. [172,173] studied retention of CO2 injected into the ocean by using three-dimensional ocean general circulation models. Ametistova et al. [174] reported that for an efficient storage, the injection has to be performed at depths more than 1000 meters. Sarv studied large-scale ocean disposal of CO_2 below 3000 m and concluded it is technologically feasible. However, injection into shallower depths has been suggested [175,176].

Effectiveness of CO_2 ocean storage depends on condition (such as rate, amount, and depth of injection), methodology and geology (such as permeability and anisotropy of disposal formations) of injection, oceanographic characteristics of the site and chemical–physical behavior of CO_2 in the marine environment [172]. Small-scale field experiments, theoretical, laboratory and modeling research of oceanic CO_2 storage has been studied for over 30 years. Notwithstanding issues of ocean circulation, storage efficiency, technology, cost, technical feasibility, international limitations regarding dumping at sea, and strong public opposition, ocean CO_2 storage would result in a measurable change in ocean chemistry, with corresponding consequences for maritime life and causes negative effects on marine ecosystems. Lack of sufficient knowledge about the consequences of this process on the marine life cycle would be a challenge.

3.3.2. CO_2 capturing and injection for EOR purpose:

Injection of CO_2 into oil and gas fields for enhanced oil recovery (EOR), not only to sequester CO_2, but also increases the production of crude oil, which is employed since 1960s. EOR increases annually as much as only 84 research and commercial projects in 2000 were in operation worldwide [110,111,112,177,178]. Despite mature technology of enhanced oil recovery, the cost of CO_2, the price of oil and the location of the reservoir in relation to the CO_2 source affect the economics of this process [179]. Iran as OPEC's second-largest oil producer possesses substantial reservoirs of hydrocarbons. At the end of 2011, oil production of Iran reaches 1439 million barrels per day (mbd), about 5.4% of world total, and ranked 4th oil producer. Iran aims to seek foreign investment to raise its oil production to eight million barrels per day by about 2025 [180]. Furthermore, Iran produces 149 billion cubic meters (bcm) of natural gas, 4.4% of the world total. It is estimated that over 120 billion cubic meters of natural gas will be needed yearly by 2015 in order to maintain Iran's oil production. Nevertheless, in 2010, only 88.4 million cubic meters of natural gas are injected into oil fields, which have a growth rate of 11.9% relative to the previous year. This amount is far below 200 million cubic meters of natural gas, which will be needed daily by 2015 for EOR in order to maintain oil production.

Table 5 shows the amount of gas injections into fields in Iran during previous years. Iran has the best opportunity for transfer gases into oil fields in Middle East countries, due to substantial natural gas-reservoirs, well geographical distribution and major power generation capacity as well as CO_2 emission [181]. Ministry of Petroleum in Iran has 34 gas injection projects in south which 18 projects in National Iranian South Oil Company, and seven projects in Iranian Central Oil Fields Company, and the rests are related to other regions. In addition, the development project in phases 6, 7 & 8 in the South Pars gas field and construction of 6th and 7th Iran Gas Trunk line (IGAT6 & 7) for gas injection into the oil wells to enhance the recovery coefficient of the Aghajari oil

Table 5
The amount of gas injection into Iranian oil fields during previous years.

Year	2004	2005	2006	2007	2008	2009	2010
Gas (MM m^3/day)	80.05	77.25	73.05	87.70	77.74	79.01	88.40

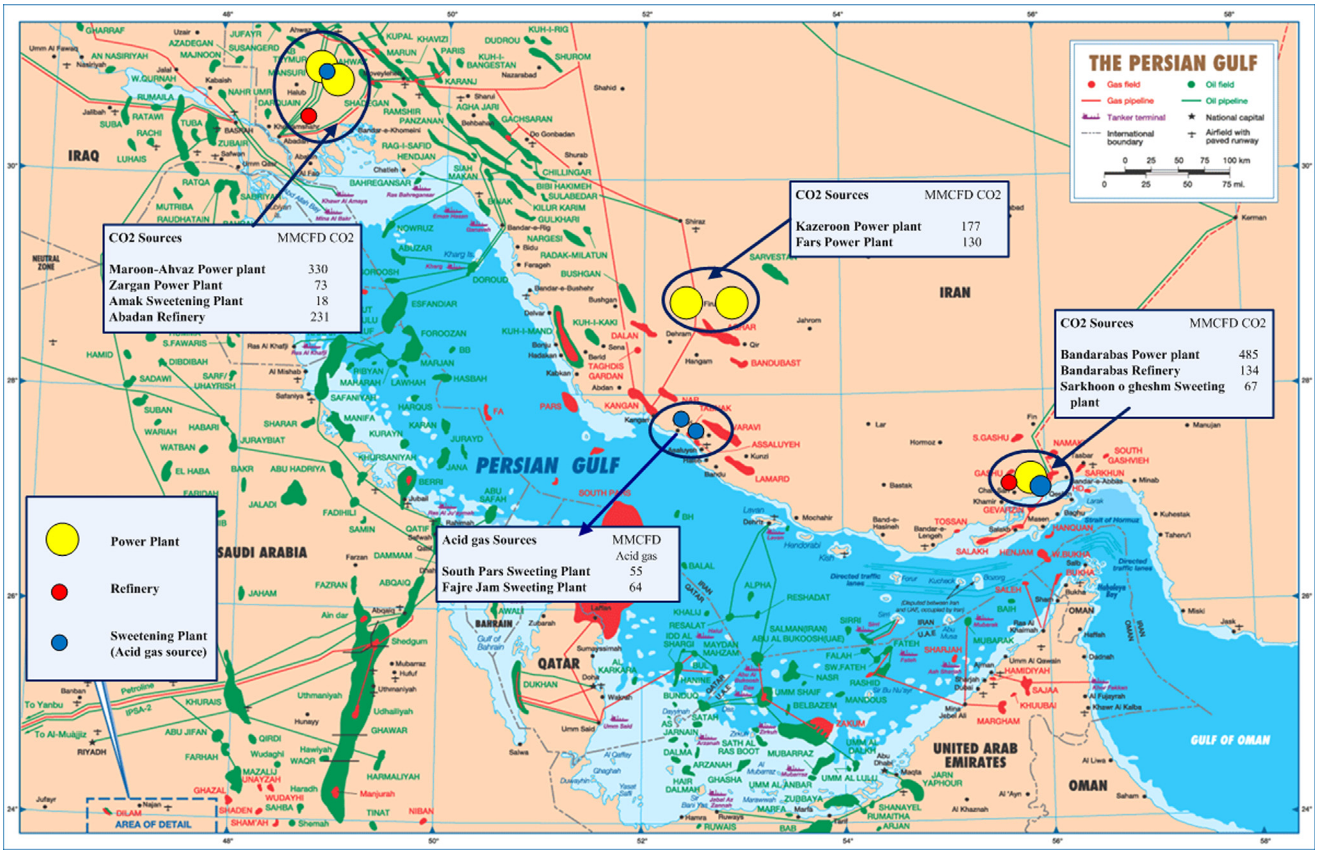

Fig. 3. Geographical distribution of major stationary sources in Southern Iran.

field are considered. Besides, two water injection projects into Resalat and Reshadat fields will be implemented.

Iran's injection of natural-gas for EOR probably will be reduced due to the increased level of domestic and export demands for natural gas and thus CO_2 can be substituted instead of this amount of natural-gas portions. However, only nearly 12.5% of the gas required for injection is equivalent to CO_2, which is produced in power plants close to oil fields with relatively short pipelines for CO_2 transport. Nevertheless, the rate of CO_2 produced by power plant increases annually, and it will be a chance for Iran by using CO_2 in EOR to reduce greenhouse gases and natural gas for EOR and increase its oil production. Approximately, it is estimated that in regard to oil well structure and the pressure of operation, 2 to 8 barrels of oil enhanced with one tone of CO_2 injection [19].

Iran's CO_2 emission has increased from 492.3 million metric tons in 1994 to 532.4 million tons in 2010, and just power plant's emission can be raised to 247 million tons in 2015. Carbon dioxide Capture and Storage (CCS) projects are a way to avoid environmental challenges caused by this increase in CO_2 emissions. Some of the power plants are located in south of Iran, near to major oil fields and according to screening criteria, are good candidates for CO_2 injection such as Bandar Abbas 485 MMcfd CO_2, Maron Ahvaz 330 MMcfd CO_2, Kazeron 177 MMcfd CO_2, Fars 130 MMcfd CO_2 and Zargan 73 MMcfd CO_2. Geographical distribution of these stationary sources is shown in Fig. 3.

Major gas field, South Pars, is located in south of Iran, which in 2005, the amount of natural gas for injection in this field was 11.173 million m^3/day, whereas only 2.653 million cubic meters of associated gas were available in the nearby fields. Until 2020, the associated gas needed for re-injection will be approximately 5.44 million cubic meters per day with considering the expansion project planned, which is far below the amount needed for EOR as mentioned above [48]. Most onshore reservoirs were located in the Khuzestan Province in south-west of Iran. There are large stationary sources of carbon dioxide emission at reasonable distances from this field. The capacity of 20 main mature oil fields in South Part of Iran for carbon storage is estimated more than 16 Giga ton CO_2 equivalent to 20 years current annual emission of Iran power plants [182]. The oil fields in Khuzestan and Zagros were studied by Amini Arash and concluded that Bibihakimeh, Aghajari, Ahvaz oil fields in Zagros's sedimentary basin were initial suitable locations for EOR-CO2 because of decreasing the pressure.

Additionally, the same result was achieved in Mond, Mangasht, Yadavaran and Azadegan oil fields in Zagros due to oils with low API. Khangiran gas field of which is located in Koppeh Dagh sedimentary basin has acidic gases and because of it, he concluded that it could be proper for this process [183].

Fractured carbonate reservoirs are the majority of Iranian reservoirs, which are mostly oil and mixed wet and contain more than 30 billion barrels of oil. It is difficult to produce oil from these reservoirs. Even usual production mechanisms like water injection and countercurrent imbibition do not work. Due to the dominant role of gravity force during a gas injection process in fractured reservoirs and relatively low MMP of CO_2, Fatemeh Kamali et al. [184] reported that miscible CO_2 injection can be considered as an efficient enhanced oil recovery (EOR) method for the field in southwest of Iran, Asmari formation, which is a hydrocarbon bearing fractured reservoir. Moreover, Sh Kord et al. [185] gathered the data pertaining to 10 Iranian southwest reservoirs and compared to standard screening criteria. They reported that CO_2 flooding was considered as the most efficient EOR method for the persian carbonate reservoirs. In addition, Sayyed Ahmad Alavian et al. [186] studied enhanced oil recovery (EOR) potential for carbon dioxide injection in the naturally fractured Haft Kel field, Iran. They concluded that by current reservoir pressure of 1,500–1,800 psi, oil recoveries from CO_2 injection approach 90% for

reservoir pressures of 1,400 psi and higher, whereas 15–25% recoveries reported for gas-cap expansion and/or injection of hydrocarbon (HC) gas. It is important to make a full field and pilot study in order to select the proper EOR method. According to carbon capture screening criteria of the IOR Research Institute at R&D Directorate of NIOC, which were done for the major power plants (Table 6), four power plants were selected through this process; Ramin, Zargan, Kazeroon and Fars. These criteria include distance from the reservoir, the amount of CO_2 emission, CO_2 concentration in the flue gas, power system compatibility with recycling, continuity of CO_2 production, the amount of impurities in the combustion products, access to accessories required for installation of recycling systems and power plant life (25 to 30 years).

In site selection for injection of CO_2, a parameter such as the miscibility of the gas with oil is important. Mohammad Soltanieh et al. [19] collected information of 11 reservoirs and found only 5 of them are suitable reservoirs for CO_2 injections due to the distance to major sources of CO_2 emissions and the type of reservoir and because of viscosity of oil, three of reservoirs, which have very small viscosities, found unsuitable for this purpose. They are recommending that the saturation of oil should be more than 30% to have effective EOR.

Among different reservoirs that Mohammad Soltanieh et al. [19] studied, Ahwaz reservoir due to higher saturation is a good candidate for CO_2 injections and estimated this reservoir can store up to 1,400 million tons of carbon dioxide [19]. Therefore, they studied CO_2 injections in the Ahwaz oil fields from Ramin's power plant with actual production capacity of 1748 MW, which is located at 25 kilometers northeast of the city of Ahwaz. This plant consumes 70,000 cubic meters of natural gas per hour, which produces about 4.8 million tons of CO_2 yearly. They estimated about 3.92 million tons (81%) can be captured and stored in Ahwaz oil fields. The economic study of the IOR Research Institute at R&D Directorate of NIOC was done for Ramin's power plant for 100 ton CO_2 per day and estimated the capture cost around 20$ per ton of CO_2. In some cases, CO_2 capture cast does not take into account the benefit gained from EOR nor does it take into account the environmental benefits as a result of CO_2 avoided.

It is estimated that one per cent of EOR is equivalent to approximately 5.8 billion barrels of improved enhanced oil recovery. Thus, Iran instead of considering the estimated its oil reservoir, even Iran can provide a network for the transfer and trading CO_2 in Middle East countries. It is obvious that the economy of EOR with CO_2 becomes more favorable with the increasing price of oil and the possibility of utilizing the Clean Development Mechanism (CDM) of the Kyoto Protocol [187]. Despite these benefits, until now, any project of EOR with CO_2 has not been employed in Iran. Whereas in other regions, investments for EOR projects increase annually: for example, in 2008 with cooperation between the governments of Japan and China, more than 40 Mt of oil is produced from the oil field annually in carrying out a project to inject CO_2 emitted from the Harbin thermal power plant in China into a Daqing oil field and in 20011 by using CO_2 for EOR in this oil field between 270 and 1300 million barrels of oil could be recovered [179,188].

3.3.3. CO_2 Storage in underground formations:

The world's first operation injection CO_2 into saline aquifers was performed in 1996 at Sleipner in the Norwegian part of the North Sea [114,115,189]. The potential of the three primary carbon storage options has been explored by the International Energy Agency's (IEA) Greenhouse Gas R&D Program and the Intergovernmental Panel on Climate Change, and the results are tabulated below.Table 7

As shown in the above table and other studies, deep saline aquifers have the highest potential capacity for CO_2 storage compared to the other major options [30,163,191]. Many factors must be taken into consideration in the selection as a site which is the crucial part in carbon storage. Porosity, permeability, injectivity, accessibility, capacity and storage security are properties of the storage rock and seals which must be considered. There are many underground geological formations in Iran that could potentially be used to store CO_2, which is briefly described. The major structural zones can be distinguished in Iran are Zagros, the second large basin in the middle east, central of Iran (comprises three major domains the Lut Block, the Kerman-Tabas Block, and the Yazd Block), Koppeh Dagh, Southern Caspian, Sanandaj-Sirjan Zone, which extends over 1200 km length, Alborz Mountains, and East Iran/Mark ran [192]. Fig. 4 shows the location of these structural zones in Iran.

Zagros Structural Zone, with an approximate surface of 553000 square kilometers, comprises Folded Zagros in the southwestern part of the Zagros which consists mainly of thick marine sediments of several thousand meter depths and the High Zagros which its width varies around 10 to 65 km. There are also several underground options for storing CO_2 in each basin. Coal layers, salt domes, underground sour water formations and oil and gas reservoirs are options for Iranian basins which each of them has benefits and drawbacks [194].

Movagharnejad et al. [29] repeated due to the high cost of CO_2 storage in coal layers and salt domes and limited capacity of oil and gas reservoirs for CO_2 storage, the storage policy has to be shifted toward underground sour water formations after a certain period of time. They also mentioned that the main drawback to this option is the uncertainty of reservoir stability, which makes necessary to conduct extensive research projects before the set-up of actual processes. Desirability and potential capability are two factors, which play the important role in CCS strategy. Movagharnejad et al. [29] investigated main sedimental basins of Iran based on these two factors. They reported that Koppeh Dagh Basin had much desirability than other basins, and Zagros Basin has much CO_2 storage potential capability of sour water underground formations than other basins. Considering these potentials in Iran for storing CO_2 in saline aquifers but any research, commercial or pilot projects are not performed by the governments whereas in various

Table 6
Major Iranian power plants.

Rank	Gas power plant	Thermal power plant	Combined Cycle power plant
1	Damavand	Shahid Montazeri	Gilan
2	Hormozgan	Neka	Kerman
3	Rey	Ramin	Kazeroon
4	Sanandaj	Shazand	Neyshaboor
5	Parand	Bandar Abbas	Shahid Rajaee
6	Abadan	Esfahan	Montazere Ghaem

Table 7
Potential of Geologic Storage Options [132,190].

Geological Storage Option	Global Capacity	
	G tone CO_2	As a proportion of total emission 2000 to 2050
Depleted Oil and Gas Fields	920	45%
Unminable Coal Seams	> 15	> 1%
Deep Saline Reservoirs	400–10,000	20–500%

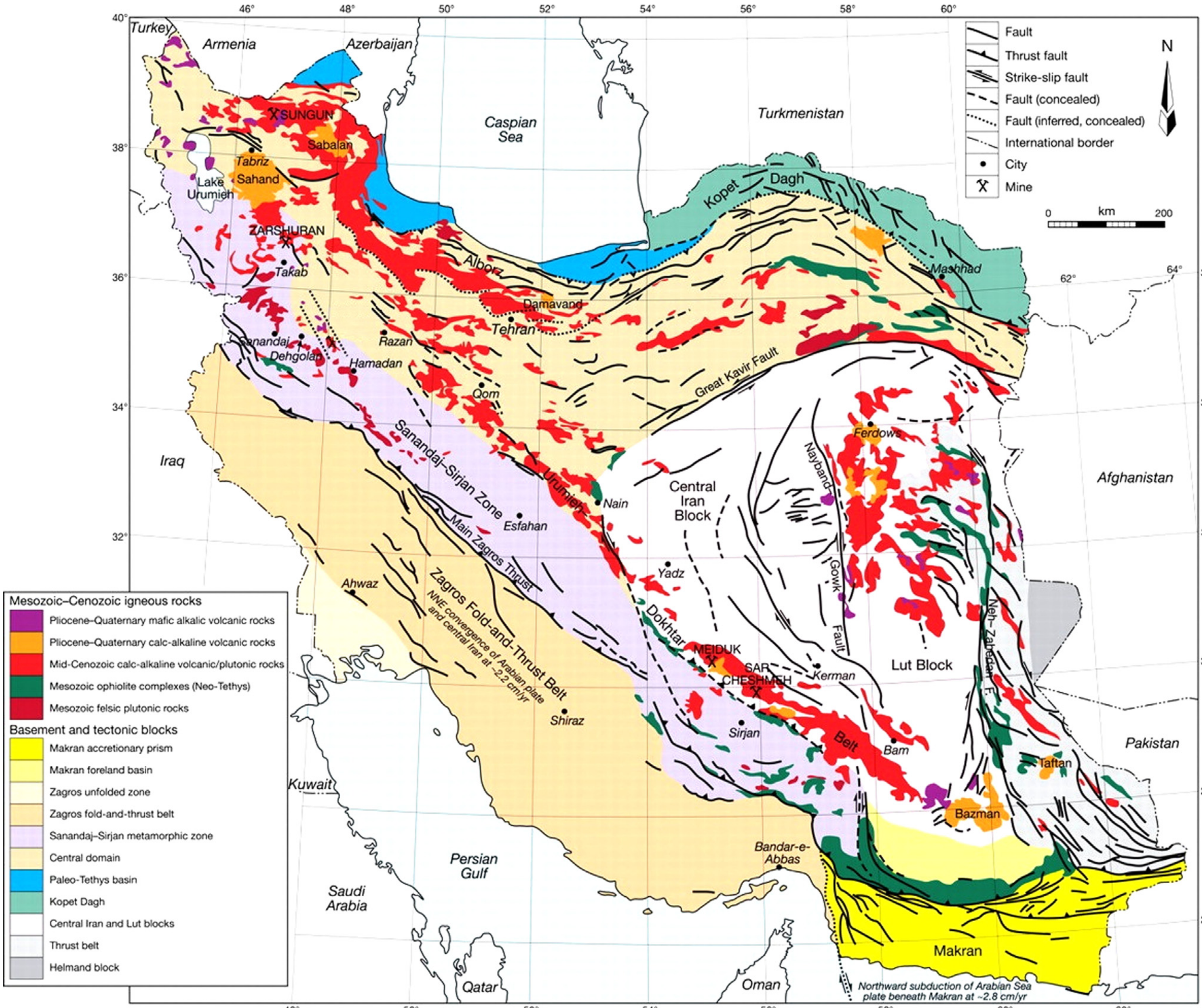

Fig. 4. Map of Iranian structural zones [193].

regions around the world by existing operations, roughly 20 Mt of CO_2 was injected into saline aquifers by the end of 2008.

Even currently total volume storage of 25 Mt CO_2 and injection rate of one Mt CO_2 per annum for a single storage operation which is the highest, until now, is recorded [130]. The largest CO_2 storage operation around the world, Gorgon in Australia, with injection rate 12,300 tons per day and total storage 129,000 kilotons will be started in 2014 [195,196]. In addition, other commercial projects in different regions were carried out such as in Salah in Krechba, Algeria 2004 with an injection rate of 3500 Mt CO_2/day and total storage 17,000 kilotons CO_2 in 2004 and Snøhvit in the offshore Barents Sea, Norway with an injection rate of 2000 Mt CO_2/day and total storage 23,000 kilotons CO_2 in 2008 [197,198].

Besides commercial project, pilot injection operations for research purposes were run in Nagaoka City, Japan between 2003 to 2005 with an injection rate of 40 Mt CO_2/day and total storage 10 kilotons CO_2, Frio in Liberty County, Texas, USA between 2003 and 2005 with an injection rate of 250 Mt CO_2/day and total storage 1.6 Kilotons CO_2 and Ketzin, Brandenburg, Germany between 2008 to 2010 with an injection rate of 86 Mt CO_2/day and total storage 60 Kilotons CO_2 [199–201]. Although oil and gas reservoirs for CO_2 storage have limited capacity, but they have a number of attractive features such as low exploration costs, well known geology and have held liquids and gases for millions of years, and they are proven traps. Besides of these features, potential to re-use some parts of the hydrocarbon, and the benefits gained from oil productions.

4. Microalgae and biomitigation of CO_2:

Although carbon capture storage (CCS) technologies can capture CO_2 from CO_2 sources and the flue gas such as power plants and cut emissions, but these technologies still cannot decrease the CO_2 that has been added to the atmosphere. If there is no need to extract all the CO_2 out of the air, it is the advantage of capturing CO_2 from the air, because of a fraction of CO_2 in the air is required to prevent the earth's temperature from the freezing temperature of 273 K. Nevertheless, the concentration of CO_2 in the atmosphere by the large-scale capture of CO_2 from the air could reduce [202,203]. Over the long term, the viewpoint of capturing CO_2 is changed from managing climate risks to a renewable-energy source, such as by using microalgae, and then the carbon cycle through the atmosphere is completed by the process of recapturing CO_2 from the air [204–206].

Therefore, another method for mitigation carbon dioxide is growing algae due to their application for recycling of exhaust flue carbon. The use of algae for this purpose is not new, having been

suggested as early as 1955 [207]. Recently, biological CO_2 mitigation which carried out by plants, and a photosynthetic microorganism has attracted much attention as an alternative strategy because it leads to the production of biomass energy during the process of CO_2 fixation through photosynthesis [208].

As compared to biofuels produced from cellulosic or microbial biomass, CO_2 fixation capacity combined with energy generation from microalgal biomass are much preferable [209–216]. Heavy-metal removal and waste-water treatment are other environmental protecting processes by microalgae [217,218]. Generally, flue gas, commercial carbon dioxide and the air are three sources of CO_2 for cultivating microalgae [219–221]. Commercial CO_2 in contrast with its wide availablity, because of its non-continuous availability, increasing microalgal production costs and decreasing the potential of using microalgae to mitigate CO_2 levels in the air, should not be a priority for the microalgal cultivation process [222,223]. Thus, flue gas could be another source of CO_2 for microalgal growth [224]. Nutrients, nitrogen and phosphate source, trace metals, water, CO_2 and sunlight are their requirements. Algae utilizes these resources very efficiently and has high productivity with relatively low water consumption in comparison wih terrestrial plants. These requirements can be controlled and optimized for maximum oil yields and biomass [225].

The important elements which constituting the microalgal cells are carbon, nitrogen, phosphorus, sulfur and inorganic salts, which include magnesium, iron, trace elements and in some cases, silicon [226]. A balanced medium should be developed for optimum microalgae growth and CO_2 fixation [227]. For example, in many *Chlorella* strains such as *Chlorella capsulate*, *Chlorella minutissima*, *Chlorella luteoviridis*, *Chlorella emersonii*, *Chlorella pyrenoidosa* and *Chlorella vulgaris* lipid content can be increased by nitrogen limitation [228]. Moreover, under nitrogen deficient conditions, in *Nannochloris sp*. cells 2.2 times of that in nitrogen sufficient culture triglycerides could be accumulated and in the same condition, 35–54% lipids with 80% triglycerides component could be accumulated in *Neochloris oleoabundans* cells [229,230].

Temperature is another major factor which can generally accelerate the metabolic rates of microalgae and reduction of it leads to inhibition of microalgal growth [231]. The optimal temperature for growth has been reported 25–35 °C and maximum cell densities achieved around 30 °C for many species [232,233]. Although some species under acidic (such as *C. littorale*) or alkaline (such as *Spirulina platensis*) conditions have optimum growths, neutral pH is suitable for most microalgal species [234,235]. It is obvious that pH of growth medium can be controlled by adjusting CO_2 and NH_4 concentrations. The main source of energy for microalgae strains is sunlight. Typical microalgal cells require relatively low light intensity compared to higher plants [236]. Increasing light intensity lower than 400 mmol $m^2\ s^{-1}$ can usually increase microalgal metabolic activity rates [231]. Due to the slow growth rates of conventional terrestrial plants, the potential for increased CO_2 capture in agriculture by plants has been estimated to contribute only 3–6% of fossil fuel emissions [237].

While microalgae have the ability to fix CO_2 due to fast growing while capturing solar energy with efficiency 10–50 times greater than that of terrestrial plants and also among this process, they can produce biomass for the subsequent production of biofuels and other valuable products [238,239]. Usually algae with low oil contents grow relatively fast. For example, algae containing 30% oil may divide three times daily, whereas algae containing 80% oil will only divide once every 10 days [240].

Although strains are starved of nutrients, grow slowly but they are capable of producing large amounts of Lipids. When one gram of microalgae biomass produces 1.6 to 2 grams of CO_2 is captured [241]. Directly passing flue gases through the aqueous environments of microalgae growth and no cost of separating other elements in flue gas can be a very efficient way of capturing the CO_2 in those streams [242]. There are many reports on utilizing the CO_2 emitted from fossil-fuelled power stations by algae or other industrial sources of CO_2 such as cement processing.

4.1. Algal chemical composition:

Algae made up of eukaryotic cells and have plastids, bodies with chlorophyll that carry out photosynthesis. Nevertheless, chlorophyll molecules are different in various strains of algae; some have only Chlorophyll A, some A and B, while other strains, A and C [243]. Proteins, carbohydrates, and natural oil are three main components of algae biomass. Although the mechanism of photosynthesis in microalgae is similar to other plants, due to the efficient conversion of solar energy, access to water, CO_2, and other nutrients, compared to terrestrial oilseed crops, they have an ability to produce 30 times the amount of oil per unit area of land [244–251]. The percentages of fatty acids vary with the type of algae, and some types of algae are comprised of up to 40% of their overall mass of fatty acids [240]. Lipid content of microalgae is similar to the compositions of vegetable oils and has been reported for 85% of the dry weight which exceeds the most terrestrial plants. Esters of glycerol and fatty acids with a chain length of C_{14} to C_{22}, which may be either saturated or unsaturated are lipid compositions of microalgae [252].

These fatty acids (oil) can be converted to biodiesel through transstrifecation reaction with alcohols. Therefore, because of making biodiesel from oil, widespread interest in algae oil is more recent. Although in cosmetic industry, algae oil is primarily produced from macroalgae such as oarleaf seaweed [253,254], but recent research on oil extraction from algae has been focused on microalgae [255].

4.2. Selection of optimal microalgae species for CO_2 sequestration:

More than 100,000 strains of microalgae in the world are known [253]. Cultivation microalgae and cyanobacteria for CO_2 sequestration has been examined and used such as *Spirulina sp*., *Chlorocuccum littorale*, *Scenedesmus sp*., *Chlorella vulgaris*, *Chlorella kessleri*, *Chlamydomonas reinhardtii* and *Botryococcus braunii* [222,256–263]. Research for selection of optimal microalgae species for realizing workable biological CO_2 fixation systems are vital and still under way. The criteria used for selecting microalgae species for CO_2 sequestration systems will be commercial values, high CO_2 tolerance, high-temperature tolerance, CO_2 assimilation ability, light condition and tolerance on trace elements in the flue gas such as NO_X and SO_2.

For large scale, species which can grow well under the natural day–night cycle and use the CO_2 in flue gas are preferred [8,264]. Some microalgae species have commercial values and commercial profit from biomass production will offset overall operational costs such as Chlorella, Spirulina and Dunaliella [265,266]. Efficiency of microalgal photosynthesis decreases with increasing temperature in order to significant reduction of CO_2 solubility [267]. De Morais MG et al. [260] observed that when *Scenedesmus obliquus* and *Spirulina sp*. were cultivated in a temperature controlled three stages serial tubular photobioreactor at 30 °C, have better capacities to capture CO_2. For CO_2 mitigation from flue gases the uses of thermophilic species such as Cyanidium caldarium which has a high - temperature tolerance and can grow in temperature ranging from 42–100 °C due to reduction of cooling costs are being considered [268,269]. In addition, Miyairi reported that *Synechococcus elongates* could grow under 60 °C and 60% CO2 [270].

Besides utilizing high-temperature tolerant species have a disadvantage of increasing loss of water due to evaporation. Wang B et al. [271] recommended *Botryococcus braunii* SI-30, which can produce high hydrocarbon concentrations for combined CO_2

mitigation and biofuel generation. *S. obliquus* SJTU-3 and *C. pyrenoidosa* SJTU-2 can accumulate greatly total lipids and polyunsaturated fatty acids in high CO_2 levels (30–50%) [272]. Accumulation of the total lipid content of species under same condition is different. For example, Chan Yoo et al. [249] cultivated *Botryococcus braunii*, *Chlorella vulgaris* and *Scenedesmus sp*. with 10% CO_2 to mitigate and produce biodiesel and suggested *Scenedesmus sp*. for reduction of CO_2 due to 2–8 times biomass productivity higher than that of *C. vulgaris* and *B. braunii*. However, he concluded that *B. braunii* was more suitable for production of biodiesel because of 2–4 times total lipid contents higher than that the other two strains.

Flue gas injection on microalgal growth causes a 30 % increase in biomass productivity because of the presence of nutrient in (sulfur and nitrate) the flue gas and inhibition of photorespiration by high CO_2 concentrations [273]. Photorespiration process which occurs largely in the presence of light decreases efficiency of photosynthetic carbon fixation by 20–30% [44,274]. Capability of microalgal CO2 fixation should positively correlate with their light utilization efficiency and cell growth rate due to the photoautotrophic growth of cells [275,276]. CO_2 fixation ability of 25 migroalgal strains reported in literature was compared by Shih–Hsin et al. and concluded most of them have microalgal–CO_2 consumption rates of 200–600 mg L^{-1} d^{-1}.

However, some achieved more CO_2 removal rates, such as *Synechocystis aquatulis* (1500 mg L^{-1} d^{-1}), *Botryococcus braunii* (1000 mg L^{-1} d^{-1}), *Chlorococcum littorale* (900 mg L^{-1} d^{-1}) and some *Chlorella sp.* (700–1800 mg L^{-1} d^{-1}) [220,222,258,260,261,263, 275,277–287]. Moreover, some species exhibited remarkable considerable CO_2 fixation ability such as *Anabaena sp.* (1450 mg $L^{-1}d^{-1}$), *Aphanothece microscopica Nageli* (5435 mg L^{-1} d^{-1}) and *C. vulgaris* (6240 mg L^{-1} d^{-1}) [222,239,275].

It should be attended that experimental conditions, such as CO_2 concentration, temperature, culture of growth, light intensity, and the photobioreactor designs for this comparison are different, and it may affect CO_2 fixation ability. The primary emission of flue gases is CO2, at between 3% and 15% concentration for power station, 20% and 27% for iron and steel blast-furnace gas, 13% and 33% of cement plant, 8% and 15% for oil refinery, greater than 85% of ethanol plants and larger than 95% of ammonia plants. However, these concentrations depend on fuel sources and design of the plant.

For example, coal-fired power plants generally having higher CO_2 emissions than 15%. Presence of high concentration of CO_2 in flue gases leads to increase in PH, and some species cannot tolerate this condition. Some species have been tested under great CO_2 concentration and known as high CO_2 tolerant species such as *Scenedesmus sp.*, *Chlorococcum littorale* which could grow under 80% and 60% CO_2, respectively [288,289]. Even some species such as *Cyanidium caldarium* and *Cyanidium* can grow in pure CO_2 [269,290]. However, a maximum growth rate of *Chlorella sp. T-1*, *Scenedesmus sp.* was observed under 10% and 10–20% CO_2 concentration. Another high CO_2 tolerant species, *Euglena gracilis*, can grow under 45 % concentration of CO_2 and did not grow over this condition. On the other hand, it has the best growth with 5% CO_2 [291]. Research about CO_2 tolerance of *Chlorella sp.* which has commercial values is different. For example, Hanagata et al. [289] observed that *Chlorella sp.* could grow under 20% CO_2 conditions. On the other hand, Yue and Sung et al. [279,292] could harvest *Chlorella sp*. at 50% CO_2 with biomass productivity of 500 and 386 mg L^{-1} d^{-1} and CO_2 consumption rates of 940 and 725 mg L^{-1} d^{-1}, respectively.

Even Maeda et al found a strain of *Chlorella sp. T-1* which the maximum growth rate occurred under a 10% concentration, but it could grow under 100% CO_2 [293]. Additionally, *Chlorocuccum littorale* under 50% CO_2 concentration could achieve biomass productivity of 44 mg L^{-1} d^{-1} and CO_2 consumption rate of 82 mg L^{-1} d^{-1} [259]. Oxides of nitrogen (NO_X) and sulfur (SO_X) and also metals present at much lower levels, nickel (Ni), vanadium (V) and mercury (Hg), are other constituents of the flue gases have to be considered, again depending on the fuel used. Furthermore, some researchers considered the effect of trace acid gases such as NO_X and SO_2 on CO_2 sequestration by microalgae [293–296]. Some studies using either gas mixtures that simulate flue emissions or actual flue gases reported that NO_X levels presented in flue gases pose no problem for algal growth [278,293,297–301].

Yoshihara et al. [295] reported that *Nannochloris sp*. could grow under 100 ppm of nitric oxide (NO). Nagase et al. [294] observed that *Dunaliella tertiolecta* could remove 51 to 96% of nitric oxide under 1000 ppm of NO and 15% CO_2 concentration depending on the growth condition.

Matsumoto et al. [296] reported that *Tetraselmis sp*. could grow with actual flue gas with 185 ppm of SO_X and 125 ppm of NO_X in addition to 14.1% CO_2. Moreover, Maeda et al. [293] could harvest *Chlorella sp*. under 50% CO_2, 60% NO_X and 20% SO_X with biomass productivity of 950 mg L^{-1} d^{-1} and CO_2 consumption rate of 1790 mg L^{-1} d^{-1}. Some studies show when the flue gas concentration of SO_X is above 400 ppm due to the formation of sulfuric acids and decreasing the pH of the culture can become a problem for some species [278].

Nannochloris sp. and *Nannochloropsis sp.* were harvested under 50% SO_X and 15% CO_2 with biomass productivity of 350 and 300 mg L^{-1} d^{-1} and CO_2 consumption rate of 658 and 564 mg L^{-1} d^{-1}, respectively [282]. Even Lee et al. [302] could cultivate Chlorella sp. under 15% CO_2 and 60% SO_X with biomass productivity of 1000 mg L^{-1} d^{-1} and CO_2 consumption rate of 1880 mg L^{-1} d^{-1}. Moreover, some researchers reported some species are not harvested in CO_2 with- <50 ppm SO_X.

Actually, the reduction in the pH value of the culture medium due to the presence of SO_2 inhibits microalgae growth, not SO_2 presence. [303,304] Some researchers studied the effect of metals in the flue gases. For example, Matsumoto et al. [278] reported that Ni and V above 1.0 and 0.1 ppm, respectively, decrease algal productivity. Nevertheless, Kelly et al. [305] reported there is no data to suggest that Hg has any detrimental effects on microalgal growth, and it has been indicated some algae may convert Hg between forms representing a possible route to toxic remediation. So far, efforts to find the "ideal" microalgae species for CO_2 sequestration, which has commercial value and grow well under a wide range of thermal conditions and various ranges of CO_2 concentration will continue. Some microalgal strains that have been studied for CO_2 sequestration are summarized in Table 8.

4.3. Different cultivation methods: ponds and bioreactors

Over previous years, research in pilot scale for microalgae-based CO_2 fixation, biomass production and its energy utilization have been progressed [333–335]. Important role in CO_2 capture and biomass accumulation is a strategy of microalgae cultivation. A major factor in photosynthetic carbon assimilation is light intensity/periods, which have a direct relationship with an amount of productivity in the biomass and the cell growth rate, consequently, the carbon-fixation capacity [336]. By increasing the surface area and shortening the light path and layer thickness can achieve higher utilization efficiency [267].

Increasing surface/volume ratio in the photobioreactor design to enhance surface area is critical [337]. Recently, optimization of flow and mixing in PBR by using computational fluid dynamics (CFD) technique are investigated [338–340].

Light/dark cycles have a significant effect on cell growth, and Janssen et al. reported that photosynthetic efficiency decrease as the dark period was as much as 50% of the cycle time [341]. CO_2 concentration, aeration rate, residence time of bubble, bubble

Table 8
Microalgal strains used for CO_2 biomitigation in research [15,277,306,307,309].

Microalgae	CO_2 (%)	Temp (°C)	Specific growth rate (d^{-1})	Biomass productivity ($mg\ L^{-1}\ day^{-1}$)	CO_2 consumption ($mg\ L^{-1}\ day^{-1}$)	References
Chlorella sp.	50	25	N.A	500	940[a]	[277,308]
	50	25	N.A	386	725[a]	[279]
	20	N.A	5.76	700	1316[a]	[281]
	10	N.A	N.A	940	1767[a]	[279]
	10	N.A	0.252	381.8	717.8	[309]
	10	N.A	0.11	610	1147	[309]
	5	N.A	N.A	335	700.2	[283]
	2	N.A	0.492	171	857	[220]
	N.A	N.A	N.A	5410	1380	[310]
Chlorella kessleri	18	30	N.A	87	163[a]	[263,311]
	6	N.A	0.27	87	164[a]	[263]
	6	N.A	0.38	65	122[a]	[258]
Chlorella vulgaris	15	N.A	N.A	N.A	624	[314]
	10	N.A	N.A	273	612	[286]
	2	N.A	N.A	30–45	15–25	[15,312]
	Air	N.A	0.4	40	75[a]	[280]
	Air	25	N.A	24	45[a]	[280,313]
	Air	25	N.A	40	75[a]	[280,311]
	0.09	N.A	N.A	150	3450	[285]
	10	N.A	N.A	1940	250	[315]
	2	N.A	N.A	2030	430	[292]
Chlorella emersonii	air	N.A	N.A	41	77[a]	[273]
Chlorella protothecoides	2	N.A	N.A	2860	417	[303,304]
Chlorella sp. UK001	15	35	N.A	NA	> 1	[299,305]
Spirulina sp.	12	30	N.A	220	413[a]	[253,299]
	6	N.A	N.A	125–280	5–20	[256,306]
	6	N.A	0.44	200	376[a]	[251]
	6	N.A	0.42	210	394	[251]
	6	N.A	N.A	125–280	5–20	[256,306]
Spirulina plutensis	4	N.A	N.A	350	4–9	[216]
	10	N.A	N.A	2180	320	[315]
	15	N.A	N.A	2130	920	[316–320]
Dunaliella	3	27	N.A	17	313[a]	[321]
Dunaliella tertiolecta	10	N.A	N.A	2150	270	[315]
Scenedesmus sp.	10	N.A	N.A	370	Nil	[256]
Scenedesmus obliquus	6–18	N.A	N.A	60–160	10–80	[258,322]
	12	N.A	0.22	140	263[a]	[260]
	10	N.A	1.19	292.5	549.9[a]	[261]
	6	N.A	0.26	85	160[a]	[263]
	20	N.A	N.A	948	N.A	[323]
	10	N.A	N.A	1840	290	[272]
	10	N.A	N.A	3510	550	[263]
	20	N.A	N.A	2630	390	[324]
	air	N.A	N.A	9	16	[325]
Nannochloropsis oculata	2–15	N.A	N.A	490	80–150	[326]
	2	N.A	N.A	1140	N.A	[327]
Nannochloropsis sp.	15	N.A	N.A	270	508[a]	[282]
	15	N.A	N.A	2230	N.A	[328]
Botryococcus braunii		N.A	0.5	900	1000	[276]
	0.5–10	N.A	N.A	40–750	40–480	[329,330]
	10	N.A	N.A	3110	500	[315]
Chlorococcum littorale	40	30	N.A	N.A	1000	[319,331]
	20	N.A	1.8	530	900	[287]
Synechocystis sp.	Nil	N.A	N.A	900–1600	2070	[332]
Aphanothece microscopica Nageli	15	N.A	N.A	770	1440	[276]

N.A: Values are not available.

[a] CO_2 consumption is calculated from (P_{CO2}) = 1.88 × biomass productivity (P), which is derived from the typical molecular formula of microalgal biomass, $CO_{0.48}H_{1.83}N_{0.11}P_{0.01}$ [244].

size and generally enhancing air/liquid interface area are important in CO_2 mass transfer [282,342]. Specific internal static mixer and membrane-sparged device is two instances of methods which researcher using effectively raising the gas/liquid interface areas [285,343]. Besides these factors, maintaining balance between CO_2 and O_2 and removing excess O_2 from the culture system is another critical factor due to unsuitable effects on the photosynthesis rate (photorespiration) and cause cell membrane damage [267].

Optimal cell production should have large surface area, short internal light paths, external source, good mixing and mass transfer rate [344–346]. As a result, the strategy of microalgae cultivation for optimum growth is key issues to achieve a meaningful CO_2 sequestration. Heterotrophic cultivation in which microalgae consume organic carbon and nitrogen sources and release much CO_2 has been focused by some researcher. However, such cultivation is very high expensive because of carbon/nitrogen sources and energy

input [347–350]. Therefore, for large-scale commercial microalgal biomass cultivation systems, autotrophic cultivation strategy is chosen. Open pond and closed photobioreactor system are two distinctive cultural systems have been proposed for CO_2 sequestration with microalgae. Some researches under different conditions, have been done to know whether the open pond system or the closed photobioreactor system would be better for CO_2.

Low initial and operational costs and easy scale-up are apparent advantages of utilizing the open pond system. Low CO_2 fixation ability, biomass productivity, specific growth rate, photosynthetic efficiency, surface area, losing water by evaporation and being susceptible to contamination by unwanted species are the disadvantage of open systems. On the other hand, higher potential productivity due to better environmental control and harvesting efficiency, saving water, energy, chemicals and production of high-value long-chain fatty acids or proteins are some advantages of the photobioreactor systems. Difficult to scale up and high operating cost are disadvantages of the closed system [344–346,351]. On the other hand, for biofuel production, open pond is perhaps more favorable [352–354]. The typical size of open pond microalgae production systems needed to assimilate significant amounts of CO_2 is depended under different conditions and may range from 0.2 to 0.4 ha in area and 0.25 m in width [355–357]. However, there are existing large scale open pond such as the algal production systems developed by the Sosa Texcoco Co. near Mexico's city, which was 900 ha. In addition, in Florida, the wetlands constructed for the Everglades Nutrient Removal Project, which occupied 1,406 ha [240]. Some researchers reported other institutions and companies in the world for commercialization of microalgae technology and products [358–360]. Raceway pond with a closed loop of rectangular grid and recirculation channel is the most commonly used designs between various shapes and sizes of open ponds. At water depths of 15–20 cm, biomass concentrations of 1 g dry weight/L and productivities of 60–100 mg/L/day can be obtained in raceway ponds [267].

To mix and circulate the algal biomass and prevent sedimentation a paddle wheel is used. In Sendai, Japan, *Tetraselmis sp*. was cultivated in the open raceway pond tested by the Tohoku Electric Power CO, while other species, *Nannochloropsis salina* and *Phaeodactylum tricornutum* could not be cultivated continuously [296]. Furthermore, in Kona on the island of Hawaii at the Natural Energy Laboratory (NELH), *Tetraselmis suecica* has been used in an outdoor culture [361]. General design considerations before analysis of specific photobioreactor configurations are necessary for evaluation and comparison of different bioreactor designs effectively [362].

Reactor design such as plastic bags, flat plate, annular, vertical and air lifted glass or plastic tubular have been focused [280,363,364]. Tubular reactors, plate reactors, or bubble column reactors are types of closed bioreactors [267,365]. Tubular photobioreactor is a common type of closed bioreactor, which consists of an array of straight transparent tubes that are usually made of plastic or glass and are the most attractive for large-scale outdoor cultivation [343,366]. Nevertheless, CO_2 depletion, excess O_2 removal, parameter control and high cost restrict size and length of tubular photobioreactor and make difficult to scale up [367,368]. Due to the best penetrating of light and for ensuring a high biomass productivity, the diameter of the tubes is generally 0.1 m or less.

Normally, column photobioreactor compare to the tubular and plate reactor has a relatively low cost [369]. For achieving the most CO_2 fixation efficiency, some researchers utilized airlift PBRs due to their relatively better circulation and mass transfer [309,345]. On the other side, when using airlift PBRs, slow circulation time cannot decrease the effect of photo-inhibitory and small bubbles reflect more light, which decreases the photosynthetic efficiency [285,370]. Due to greater surface area, proportionately short light path and steep light-gradients, flat-plate PBRs have both relatively high cell density and CO_2 consumption ability and has no difficulties to scale up compare to tubular bioreactor [221,242,8]. Economically, open pond system relative to photobioreactors is 10 times less [253]. On the other side, photobioreactors has high biomass productivity. Nevertheless, both closed photobioreactors and open pond systems could be efficiently fixed CO_2. Moreover, other systems are utilized such as hybrid systems, which use open ponds as well as closed bioreactor in combination to get better results. Some new techniques such as a semi-continuous in outdoor bag photobioreactors are also applied to CO_2 capture by microalgae cultivation [311,371].

4.4. Sequestration of CO_2 by microalage in Iran:

As it mentioned, over 154.8 Mt CO_2 (28%) came from power plants. Therefore, mitigation of carbon dioxide from power plants can help to reduce major amounts of emissions in atmosphere in Iran. From fig. 5, it can be seen that many power plants in Iran are far from oil fields or geological formation suitable for CO_2 sequestration.

For example, Shahid Mohammad Montazeri and Shazand power plant, the third and fourth largest thermal power plant, are located approximately at central of Iran and far from major oil and gas fields. Additionally, they are far from two main sedimental basins of Iran, Zagros Basin and Koppeh Dagh Basin.

Furthermore, Shahid Salimi power plant, second greatest thermal power plant in Iran and one of the biggest power plants in the Middle East is located at Caspian Sea Coast, in Mazandaran province. This power plant is one of the strategic power plant with installed nominal capacity 1779.6 MW. Roughly, 55.3% CO_2 emissions from power plants in Iran are produced from thermal power plants and 62% nominal capacity of these power plants are produced in the provinces that are far from geological formations. Since natural gas is the dominant fuel in Iranian power plant, 73.8%, therefore, flue gases from them have little trace elements such as SO_X and CO_2. Accordingly, the composition of flue gases and directly passing flue gases through the environments of microalgae cannot cause a problem for microalgae growth. Therefore, due to the existence of warm and moderate climate, enough sunlight and even in some cases close to the sea, microalgae have suitable condition for growth. In according to distance of these power plants from geological formations, one of the options for CO_2 mitigation is the use of microalgae. Furthermore, microalgae can generate environment-friendly biofuel or other valuable products that cover many costs of the process.

Iran with an area of 1,648,000 square kilometers (eighteenth in size among the countries of the world) has enough land to cultivate microalgae. The Iranian coastline includes nearly 740 kilometers along the southern shore of the Caspian Sea in north of Iran and 2,440 kilometers along the Persian Gulf and Gulf of Oman in Iran. On the basis of recent research in Iran, the Persian Gulf and Caspian Sea can be habitat of greenish blooms of algae [372].

Furthermore, Presence of various saline lakes such as Lake Urmia, the third largest salt water lake on earth, in Iran's West Azarbaijan province, Maharlu salt lake in Iran's Fars province, Qom salt lake in Iran's Qom province and also several connected salt lakes along the Iran-Afghanistan's border in the province of Baluchestan Va Sistan has given rise to a new species of microalgae [373,374]. Fig. 6 shows the location of some of these salt lakes in Iran.

For example, in Lake Urmia several phytoplankton species have been reported such as macroscopic green alga; *Enteromorpha intestinalis*, cyanophyta; *Anabaena sp., Anacystis sp., Chrococcus sp., Lyngbya sp., Oscillatoria sp.*and *Synechocuus sp*., Chlorophyta; *Ankistrodesmus sp.; Dunaliella sp.; Monostroma sp.* and *Pandorina sp*., bascillariophyta; *Amphora sp*. and *Navicula sp., Nitzschia sp., Cyclotella sp., Symbella sp.,*

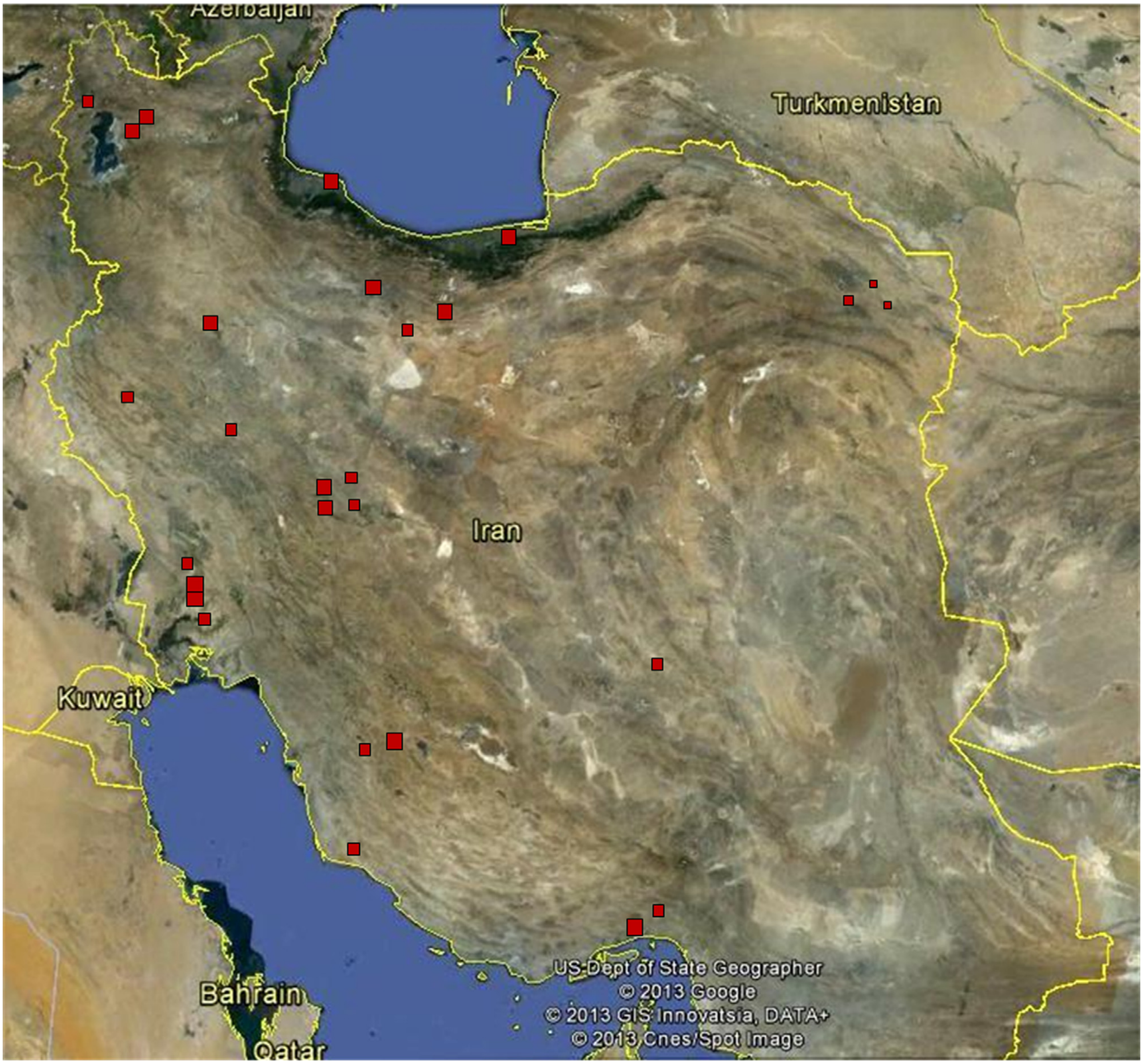

Fig. 5. Geographical distribution of CO_2 sources in Iran.

Synedra sp., Pinnullaria sp., Diatoma sp., Amphiprora sp., Surirrela sp., Cymatopleura sp. and *Gyrosigma sp.* On the other hand, the dominant specie of Urmia Lake is Dunaliella, which consists of more than 95 % of the total phytoplankton in the number [37,375–380].

Sara Rasoul-Amini et al. [252] could isolate *Dunaliella salina, Chlorella vulgaris, Scenedesmus Rubescens* from water samples collected from Maharlu Salt Lake, 30 km southeast of Shiraz, Iran. Furthermore, *Chlorella vulgaris*, *Chlamydomonas sp.* MCCS 026 and *Chlorella sp*. MCCS 040 were isolated from the rice paddy-field soil samples of Fars province in the south of Iran [381]. Mohammad Hossein Morowvat reported *Chlamydomonas sp*. for the first time as a biodiesel producer among all the microalgal strains studied for this purpose with total fatty acid content of 25% and the presence of at least nine different fatty acid methyl esters in the strain. They concluded that Chlamydomonas sp. MCCS 026 due to high growth rate, lipid content requiring just a simple and inexpensive culture medium is suitable for biodiesel production [382].

Sara Rasoul-Amini et al. [383] analyzes fatty acids' content of *Chlorella sp*. MCCS 040 and found it has highly saturated fatty acids' content, which can be an ideal candidate for biodiesel production. They used environmental isolates for biodiesel production, which may have a great and unstudied potential to be used for this purpose.

Besides salt lakes, shallow-marine limestones in the Zagros Mountains in north of Fars province have a wide and diverse range of microalgal species [373]. Also Nasrin Moazami et al. [384] isolated one hundred and forty seven marine microalgal strains from mangrove forests in the northern part of Qeshm Island. They used lab scale and open ponds to evaluate biomass and lipid productivity of microalgae strains. They concluded that *Nannochloropsis sp.* due to high biomass (50 g l^{-1}) and oil content (52%) was suitable as raw materials for commercial production.

Behrouz Zarei-Darki investigates 125 water bodies in Iran and found 182 species (198 infraspecific taxa) of blue-green algae. He recorded one hundred and nineteen species (119) (126 infr. taxa) of phytoplankton, 178 species (194 infr. taxa) of phytobenthos, and 20 species (21 infr. taxa) of periphyton [385]. He reported algal flora of rivers in Iran exhibited 891 species (1040 infraspecific taxa) from 8 divisions of algae including 111 species of Cyanophyta

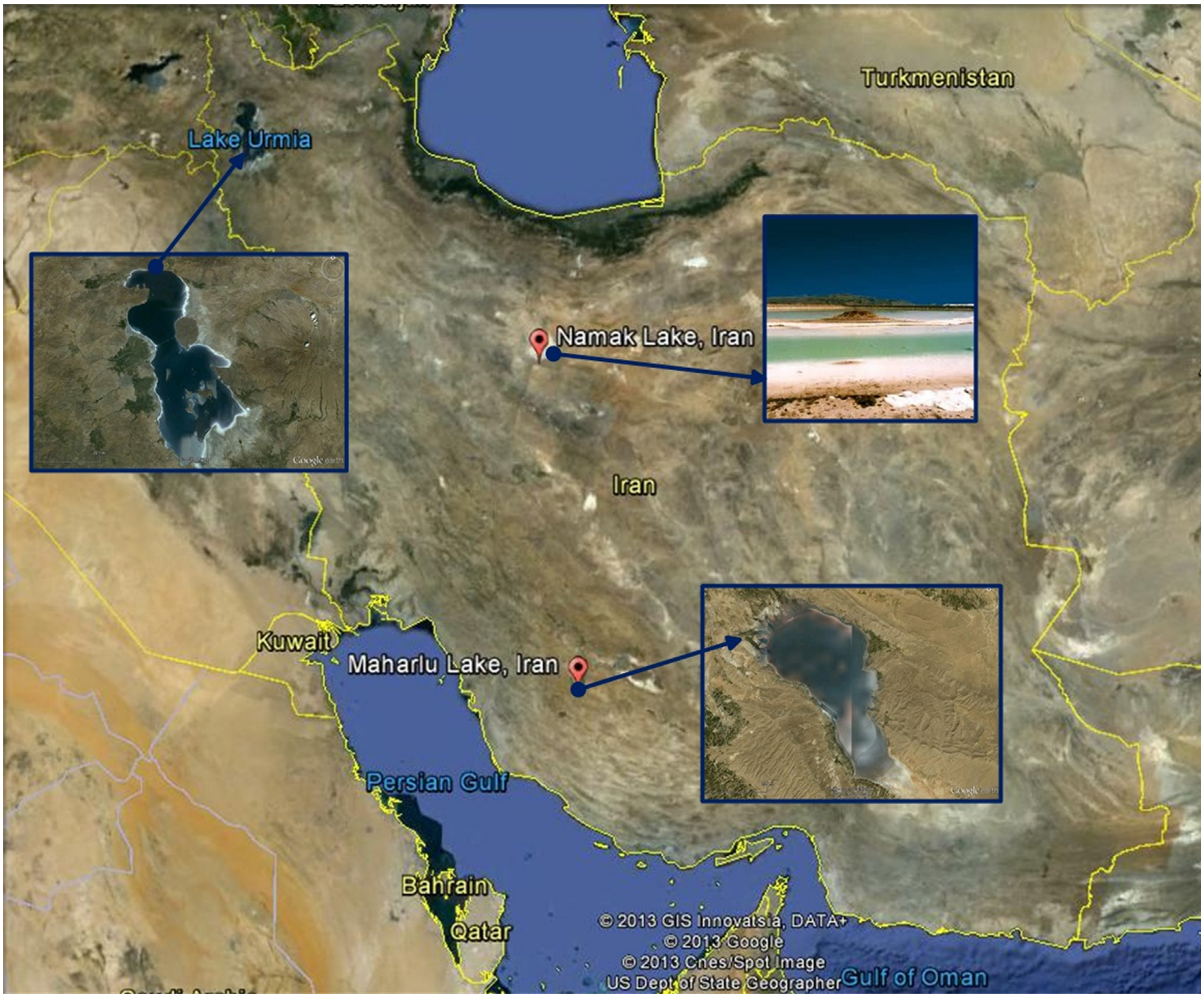

Fig. 6. The location Urmia, Maharlu and Namak Lake in Iran.

Table 9
Fatty acid content (dry weight %) of some endemic microalgal species of Iran [252,384].

Fatty acid	*Chlorella vulgaris* MCCS 013	*Dunaliella salina* CCAP 19/18	*Scenedesmus Rubescens* MCCS 018	*Nanochloropsis* PTCC 6003	Nitzschia sp.PTCC 6001
C11:0	30.5	36.1	19.8	N.D [a]	N.D
C13:0	2.4	0.2	1.9	N.D	N.D
C14:0	N.D	16.1	42.3	5.22	9.0
C15:0	6	0.5	1.5	N.D	3.5
C16:0	3.1	23.4	13.6	29.4	37.4
C16:3	2.4	N.D	N.D	N.D	N.D
C17:0	2.3	N.D	0.4	5.2	4.6
C18:0	N.D	1.3	N.D	6.6	5.3
C18:1	5.8	N.D	0.1	17.5	16.9
C18:2	3.8	N.D	N.D	23.6	11.6
C18:3	3.6	1.2	4.1	12.6	N.D
C20:0	28.2	11.1	12.1	N.D	N.D
C21:0	0.4	1.6	N.D	N.D	N.D
C22:0	0.7	N.D	N.D	N.D	N.D
C23:0	4.5	N.D	N.D	N.D	N.D
C24:0	1.9	N.D	N.D	N.D	N.D

[a] N.D: not detected.

(120 infr. taxa), 70 species of Euglenophyta (87 infr. taxa), 11 species of Chrysophyta (15 infr. taxa), 32 species of Xanthophyta (32 infr. taxa), 413 species of Bacillariophyta (511 infr. taxa), 26 species of Dinophyta (30 infr. taxa), 6 species of Cryptophyta (6 infr. taxa), and 222 species of Chlorophyta (239 infr. taxa) [386].

In the Babolrood River (Mazandaran, Iran), blue green algae and diatoms like, Anabaena, Oscillatoria, Lyngbya, Microcystis, Navicula, Nitzschia, Synedra, and Gomphonema are reported by Naser Jafari. He also revealed many green algae like, Pandorina, Scenedesmus, Stigeoclonium, Ankistrodesmus, and Chlamydomonas

[387]. T. V. Dogadina et al. [388] report 534 species and varieties of algae of Enzeli Swamp in Northern Iran, Gilan province. Species and varieties are included Cyanophyta - 68, Dinophyta -8, Cryptophyta - 9, Chrysophyta-12, Xanthophyta-23, Bcicillariophyta-232, Euglenophyta - 59, and Chlorophyta -123 taxa. Mostafa Noroozi identified 225 species from 14 classes of algae in in first Iranian land-marine the Boujagh National Park [389]. Fatty acid profile of some endemic microalgal species of Iran is displayed in Table 9.

Therefore, biological CO_2 mitigation by microalgae in Iran can be a good option to solve the problem of huge carbon emission from power. In summary, the advantages of utilizing microalgae include the following [390].

- For algae culture, high-purity CO_2 is not required. Therefore, the flue gases containing 2–5% CO_2 can be fed directly to the algal cultural systems, and this will simplify CO_2 separations from flue gas significantly and reduce costs in comparison to other CO_2 sequestration methods.
- Some trace elements such as NO_X can be effectively used as nutrients for microalgae. Therefore, there is no need to scrub the flue gas for reducing these trace elements.
- Many valuable commercial products such as B-carotene and biofuels are generated by microalgae culturing that could offset the capital and the operation costs of the process.
- CO_2 sequestration by microalage is a renewable cycle with minimal negative impacts on the environment.
- The production of oxygen from this photosynthetic sequestration would be another benefit.

At present, the cultivation of non-edible sources of cellulose and oil for the production of bioethanol and biodiesel in the Southern regions of Iran has been focused by the Biomass department of Iran Renewable Energy Initiative Council (IREIC).

This council, which comprised of seven different departments, i.e. wind and waves energy, solar energy, hydropower, fuel cells and hydrogen, biomass, geothermal energy and planning were established by Vice President of Science and Technology in 2008 [391]. The cost of capture is significant as the concentrations in the flue gas are relatively low. Only the carbon cost of 330 \$ t^{-1} could balance the costs of CCS. The carbon cost of \$270 t^{-1} established by the Kyoto protocol in 2010 cannot make CCS competitive [8]. There is not any valuable product For CCS methodology. On the other hand, the CO_2 capture by microalgae has benefits of CO2 conversion of biomass and valuable products. However, this process has high costs due to harvesting biomass, compressing air, etc. In contrast to CCS methodologies, there is not an economical evaluation to estimate the CO_2 capture by microalgae. Nevertheless, combination of CO_2 fixation, wastewater and valuable products by microalgae cultivation could be a very promising alternative to current CCS strategies [271,314,392,393].

5. Conclusion:

The importance of enhancing the natural greenhouse effect leading to changes in the climate and rise in the global average temperature by increasing concentrations of CO_2 and other greenhouse gases in the Earth's atmosphere is obvious to all and an issue of international concern and current energy policies in all countries are driven predominantly by the need to reduce carbon dioxide emission. International Energy Agency (IEA) reported that in CO_2 production, Iran in 2007 was 10th country and in 2010, was 9th country in the world. In according to the youth population of Iran, upcoming generation's needs, low energy-efficiency vectors and consumption patterns, per-capita energy consumption 15 times that of Japan and 10 times that of the European Union, it seems Iran will have a constant rise in greenhouse gases (GHGs) emissions. Besides burning of over one billion cubic meters per day acid gas in Iranian gas refineries, more than 11 billion cubic meters per day associated gases are flared, which threaten the environment and increasing them causes serious problems for human beings to live.

Therefore, mitigation policies in the energy sector are crucial to Iran's overall policies. Improving energy efficiency, fuel switching, flare gas recovery, use of clean and renewable-energy resources besides of carbon capture and storage projects are policies that Iran could utilize for CO_2 emission reduction. In Middle Eastern countries, Iran has the best opportunity for transport its CO_2 emissions into natural geological formations, because of well geographical distribution and major power generation capacity, oil and gas fields as well as CO_2 emissions. Iran has the second and third greatest natural gas and oil reservoir in the world, respectively. Furthermore, the second largest basin in the Middle East, Zagros basin, is located in Iran. Therefore, it seems that the best natural geological formations for CO_2 storages in Iran are oil and gas reservoirs and saline aquifers (sour water foundations).

The important criterion and parameter to select CO_2 sources for injection of CO_2 is the distance from reservoirs. Among energy-consuming sectors, the power plant's sector has the largest share of all CO_2 emissions. In Iran, almost 29.1% of CO_2 originates from the power plant's sector. Researchers in Iran by screening criteria indicated that four power plants, Ramin, Zargan, Kazeroon and Fars, are suitable for CO_2 capture. The disadvantages of oil and gas reservoirs for CO_2 storage are limited capacity and separation of the CO_2 from the emission streams. This method may be used for short term storage of CO_2. On the other hand, they have a number of attractive features such as low exploration costs, well known geology and benefits gained from oil production. The cost of capture is the most expensive part of CO_2 capture and storage. In Iran for accelerating and improving the CCS projects and reduction cost of capture, should move toward sweetening gas plants due to being near to geological formations, pure CO_2 produced from these plants and large volumes produced. The best sedimentary basins for CO_2 storage are Zagros Basins, the second largest basin in Middle Eastern and Koppe Dagh Basins. Sour water foundations in these basins are an optimum option for CO_2 storage in Iran.

The advantages of these basins are very higher capacity and desirability, respectively. In according to CO_2 sources and capacity, Zagros Basins may be considered as the country's most important basin for CO_2 storage. The main drawback of this method for CO_2 storage in Iran is the uncertainty of reservoir stability, which makes necessity to conduct extensive research projects before the set-up of actual processes. The main challenge of utilizing geological formation for storage of CO_2 is being widespread power plants in the country and the distance from underground formation, oil and gas fields, especially in north and central of Iran with major CO_2 sources which are far from these underground formations, such as thermal power plants, the main CO_2 emitters in power plant sectors. This study suggests that one option for mitigating CO_2 in these stationary sources is using microalgae. Due to existence of favorable climate and vast areas of Iran, microalgae have suitable condition for growth in Iran. Additionally, in according to gas share in power plant's fuel, 73.4%, emissions are cleaner from natural gas-fired plants and cleaner still in combined-cycle gas turbines. Therefore, with directly passing flue gases of power plants through the aqueous environments of microalgae could reduce the cost of carbon capture.

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